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INVESTIGATION INTO COMPATIBILITY BETWEEN REPAIR MATERIAL AND SUBSTRATE CONCRETE USING EXPERIMENTAL AND FINITE ELEMENT METHOD

Rashmi Pattnaik
Clemson University, rpattna@clemson.edu

INVESTIGATION INTO COMPATIBILITY BETWEEN REPAIR MATERIAL AND SUBSTRATE CONCRETE USING EXPERIMENTAL AND FINITE ELEMENT METHODS

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Rashmi Ranjan Pattnaik
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Accepted by:
Dr.Prasada Rao Rangaraju, Committee Chair
Dr. Serji N. Amirkhanian
Dr. W. Edward Back
Dr. David O. Prevatt

ABSTRACT

Due to the availability of a wide variety of repair materials in the concrete repair industry, with a wide range of physical and mechanical properties, selection of repair material for a particular repair of concrete is challenging. Previous studies and the available literature indicate that the failure of concrete repairs is mainly due to improper selection of repair material based on repair material properties, without investigating compatibility between repair material and substrate concrete. The compatibility between repair material and substrate concrete exists when the composite section of repair material and substrate concrete withstands all stresses induced by applied load under different environmental conditions without experiencing distress and deterioration over a designed period of time.

In this dissertation the compatibility between eight repair materials and substrate concrete was investigated in three stages. First, individual properties of the repair materials such as setting time, flow, compressive strength, flexural strength, split tensile strength, bond strength, drying shrinkage, freeze-thaw resistance, and permeability, were determined using standard ASTM test procedures. Second, the compatibility was investigated using a composite beam of repair material and substrate concrete under third point loading. Third, the correlation of repair material properties with the compatibility was investigated to predict the durability of the concrete repair. Based on these studies, a compatibility test method is proposed to examine the compatibility between repair material and substrate concrete.

In the first stage of this research, many variations in the material properties were observed among the eight repair materials. While determining the slant shear bond strength of the repair materials, it was observed that the failures of the composite cylinder specimens did not occur on the slant surface for all repair materials as selected. Those types of failure lead to different values of the bond strength for the same repair materials. Slant shear bond strength test method of ASTM C 882 is widely employed, wherein a composite cylinder prepared with repair material and substrate mortar was tested under compression. In this research the potential reasons behind the different failure patterns as observed were analyzed using experimental and finite element methods. It was observed that the bond strength of the repair materials and the mode of failures depended on the mechanical properties of repair material relative to the properties of substrate mortar. Also, the surface texture of the substrate mortar and the type of curing influenced the bond strength. Based on these findings, suggestions were made to improve the ASTM C928 specification.

In the second stage of this research, composite beams of repair material and substrate concrete were prepared and tested in flexure to simulate tensile stresses in the repaired section. Tensile stresses are generally observed at the joints and in the tension areas in a concrete structure, where the tension in the concrete repair is induced by imposed loads or due to environmental conditions. In this study the flexural strength, failure patterns, and load-deflection curves of the composite beam specimens were compared with the similar results of a control beam to assess the compatibility. In addition, the influence of three curing conditions was evaluated to determine the effect on the compatibility. Compressive strength, flexural strength, split tensile strength, and drying shrinkage of the repair materials and substrate concrete were investigated to aid in the analysis of the compatibility. In this study incompatibility of repair material and substrate concrete refers to a combination of factors such as (i) flexural strength of composite beam as compared to control, (ii) failure patterns (de-bonding and edge cracking), and (iii) behavior of load-deflection curves. It was observed that significant differences in compressive and flexural strength between the repair material and substrate concrete caused incompatible failures. In addition, high drying shrinkage of the repair materials also caused the incompatible failures.

In the third stage of this research, correlation of individual material properties, such as compressive strength, flexural strength, bond strength, and drying shrinkage, was investigated with the compatibility. Typically, the repair materials are selected based on its material properties instead of studying the behavior of composite section formed by repair material and the substrate concrete. From this study it was observed that no significant correlation of the individual repair material properties exist with the compatibility. However, among all repair material properties as investigated, bond strength had the highest correlation coefficient (R^2=0.57), and flexural strength had the lowest correlation coefficient ($R^2 = 0.01$) with the composite beam flexural strength.

DEDICATION

I dedicate this work to my wife Jyoti and to my son Manish. Their encouragement and cooperation made this research possible.

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CHAPTER ONE
INTRODUCTION

1.1. Background

Repair and rehabilitation of concrete infrastructure is an important aspect of maintenance of concrete structures in the United States and elsewhere in the world. It is estimated that the annual cost to owners for repair, protection and strengthening is between $18 billion and $21 billion in the United States alone (Emmons 2006). Durability of such repair and rehabilitation has become the biggest concern to the repair industry as well as to the end users. Repair failures and endless "repair of repairs" are observed in most places (Vaysburd et al. 2004). Substantial advances have been made in the field of repair materials, while the industry still has an unacceptable high level of defects and failures of concrete repairs (Mcdonald et al. 2002). Recent investigations of repairs to bridge decks and other structures have indicated an overwhelming incidence of premature failures resulting from a range of factors. These factors include inappropriate selection of repair materials, poor workmanship, and inadequate characterization of substrate concrete (Vaysburd 2004).

A good repair improves the function and performance of the concrete structure, whether the structure is a pavement, or a bridge, or a building. On the other hand, poor repair fails early or deteriorates the adjoining sound concrete material in a relatively short period of time. Selection of appropriate repair materials depends on the material properties and behavior of composite section under anticipated service exposure conditions (Vaysburd et al. 2000).

Previous study shows that disparity in material properties such as compressive strength, flexural strength, stiffness, Poisson's ratio, creep coefficient, drying shrinkage etc., affect durability of the concrete repair (Emmons et al. 1994). Such disparity may result in initial tensile strains that either crack the concrete repair, or cause de-bonding at the interface between repair material and substrate concrete. Both of these results (cracking and de-bonding) reduce the load-carrying capacity and durability of the concrete structure. Therefore, selecting an appropriate repair material for a concrete repair is challenging. To achieve a durable repair, it is essential that the properties of the repair materials and substrate concrete should match properly. This helps ensure that the repair material can withstand all loads and the stresses resulting from the volume changes, such as relative shrinkage or expansion for a specified environment over a design period of time, without experiencing distress or deterioration. Durability therefore, is a function not only of the basic components (material properties) of the repair materials, but also how such components and the system as a whole respond to load and to the exposure conditions of the structure.

Thousands of materials with widely varying properties are currently being marketed for repair of concrete structures. The lack of accepted industry-wide test methods for repair materials resulted in a limited available evaluation procedure that is driven more by manufacturer preferences than by a durability of the concrete repair. All too frequently, only the isolated properties of repair materials are emphasized, whereas the more important properties of the composite are neglected.

The present research investigates compatibility between the repair materials and substrate concrete using a composite beam under third point loading (see Figure 1.1), as per modified ASTM C78 test procedure. Eight pavement and bridge decks repair materials as approved by South Carolina Department of Transportation were chosen for this study. The material properties such as compressive strength, flexural strength, split tensile strength, bond strength, drying shrinkage, permeability and freeze-thaw resistance were examined. Bond strengths of the repair materials were investigated to predict the compatibility between the repair material and substrate concrete. Specimens were prepared in three different curing conditions before testing. Correlation between the individual repair material properties and the compatibility was also investigated to evaluate whether repair material properties are sufficient to predict the durability of the concrete repair.

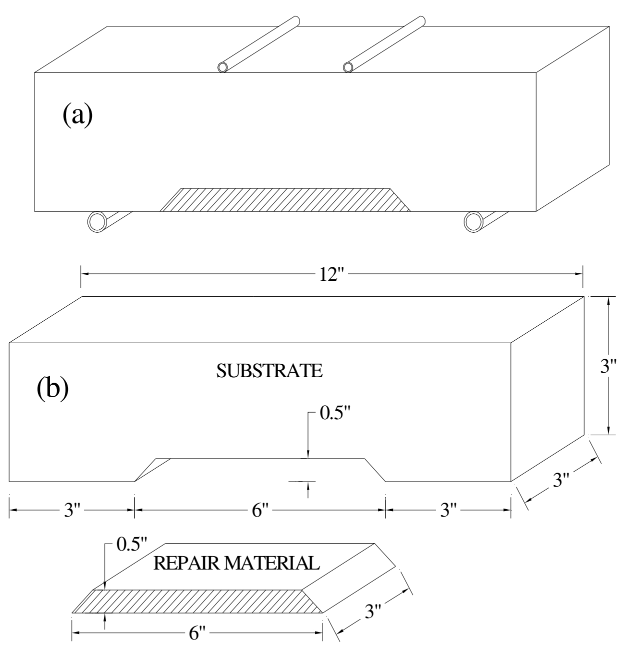


Figure 1.1 Third Point Loading Composite Beam

1.2. Research Need

From the literature review (presented in Chapter Two), it is noticed that the concrete repair is a complex process, and the current experiences with concrete repair are not satisfying. Repair materials are often perceived to lack both early age performance and long-term durability, due to the inherent brittleness and susceptibility to fracture. Many undesirable repair behaviors were observed on the field in the forms of early age surface cracking or interface de-lamination between the repair and the concrete substrate, due to relative volume change of repair material and substrate concrete. Cracking and de-lamination are the common causes of many repair pathologies. They facilitate the ingress of chlorides, oxygen, moisture, alkali or sulphates into the repaired system and accelerate further deterioration. Furthermore, the loss of structural integrity due to the cracking or the de-laminating impairs load transfer between the repair and the concrete substrate.

For users to make successful repairs with maximum life, the ACI Concrete Repair Guide ACI 546R-04 provides guidance on repair material selection, concrete substrate surface preparation and bonding methods. ASTM C928 Standard Specification for Packaged, Dry, Rapid-Hardening Cementitious Materials is widely used specification to select a repair material. Also, ACI Concrete Building Code ACI 318-02 recommends shrinkage and temperature reinforcement to control cracking. However, there is no established ACI or ASTM test method to determine the compatibility between the repair materials with substrate concrete before selecting a repair material.

The key to selecting an appropriate repair material is to understand its purpose in the repair. More often than not, many users in the repair industry believe that the simple answer to the repair problems is improving the compressive strength of the repair material or accelerating its strength gain to reduce disruption to the commuting public. However, compressive strength is not an important material property for selecting a repair material as observed in the literature review. These demands have resulted in an emergence of a range of new rapid set repair material products, not all of which perform equally or adequately.

Existing specifications do not appear to clearly identify and quantify the specific requirements for achieving long lasting durable repairs with the available repair materials. In this regard, it is important to develop a systematic approach based on specific and relevant properties to evaluate the repair materials. So, the need to conduct a compatibility study of the repair material has become more important than ever before. Repair and protection practice varies widely based upon individual beliefs, understandings, and experiences. There is no rational test method to select repair material for deteriorated substrate concrete under a particular load or environmental condition.

1.3. Research Objectives

To investigate the durability of concrete repair, the following three research objectives were examined

(i) Whether individual repair material properties would be an indicator for the durability of the concrete repairs.

(ii) Whether bond strength of repair materials can predict the compatibility between the repair material and substrate concrete.

(iii) Development of a test method to investigate the compatibility between repair materials and substrate concrete

1.4. Research Methodology

In order to accomplish the research objectives, the following five steps were carried out:

1. Determination of repair material and substrate concrete properties
2. Analysis of slant shear bond strength using experimental and finite element methods.
3. Investigation into compatibility between repair materials and substrate concrete using a composite beam under third point loading.
4. Correlate compatibility with repair material properties.
5. Develop a test method to evaluate the compatibility.

Step 1, Figure 1.2 shows the flowchart for conducting experiments to determine the material properties of the repair materials used in this research.

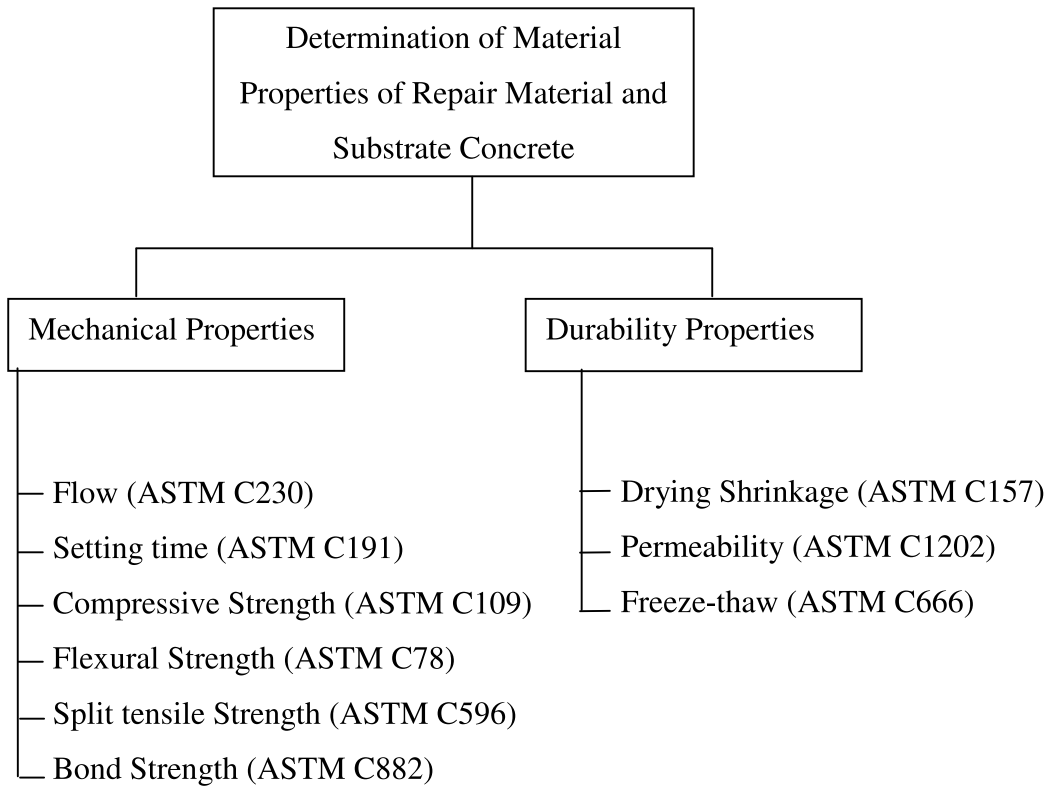


Figure 1.2 Flowchart for Determination of Repair Material Properties

Step 2, Figure 1.3 shows the flowchart for conducting the analysis of slant shear bond strength.

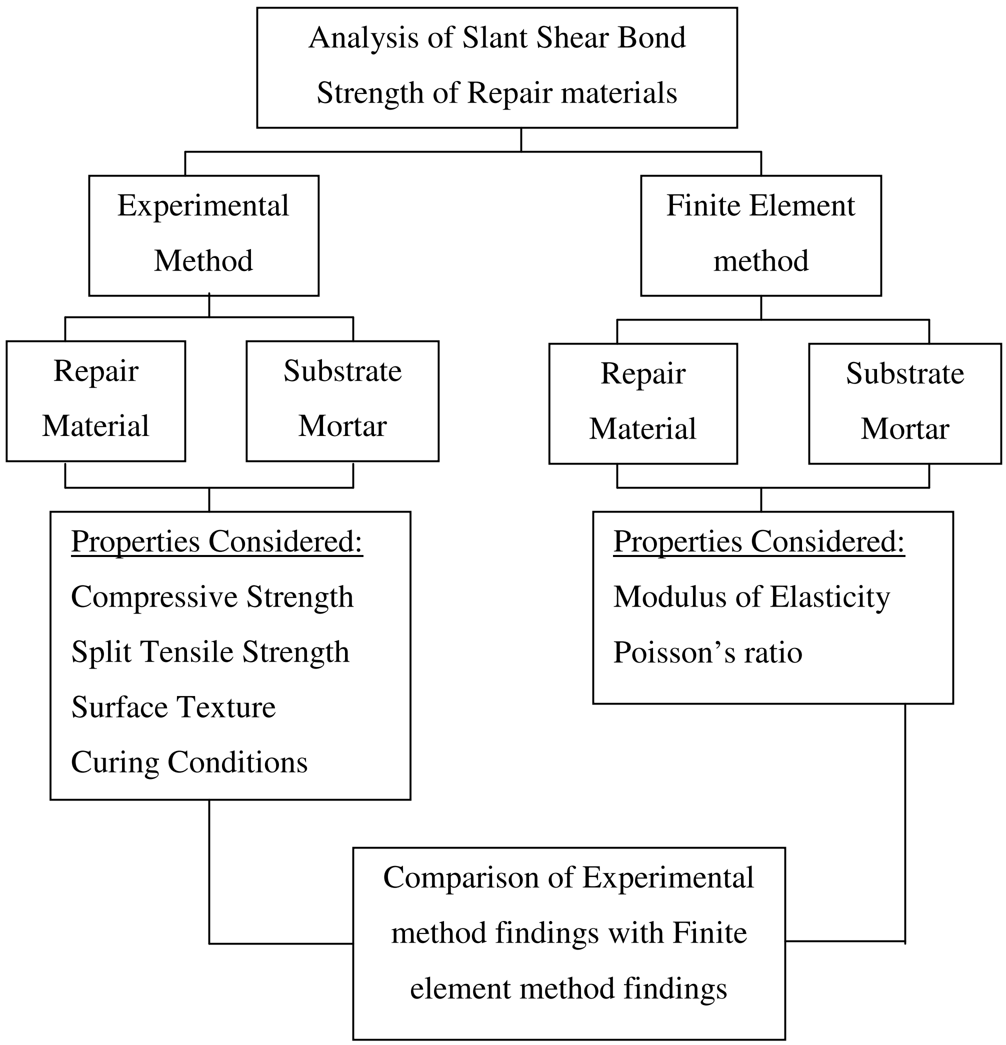


Figure 1.3 Flowchart for Analysis of Slant Shear Bond Strength

Step 3, Figure 1.4 shows the flowchart for the analysis conducted to determine the factors influencing the compatibility between repair material and substrate concrete.

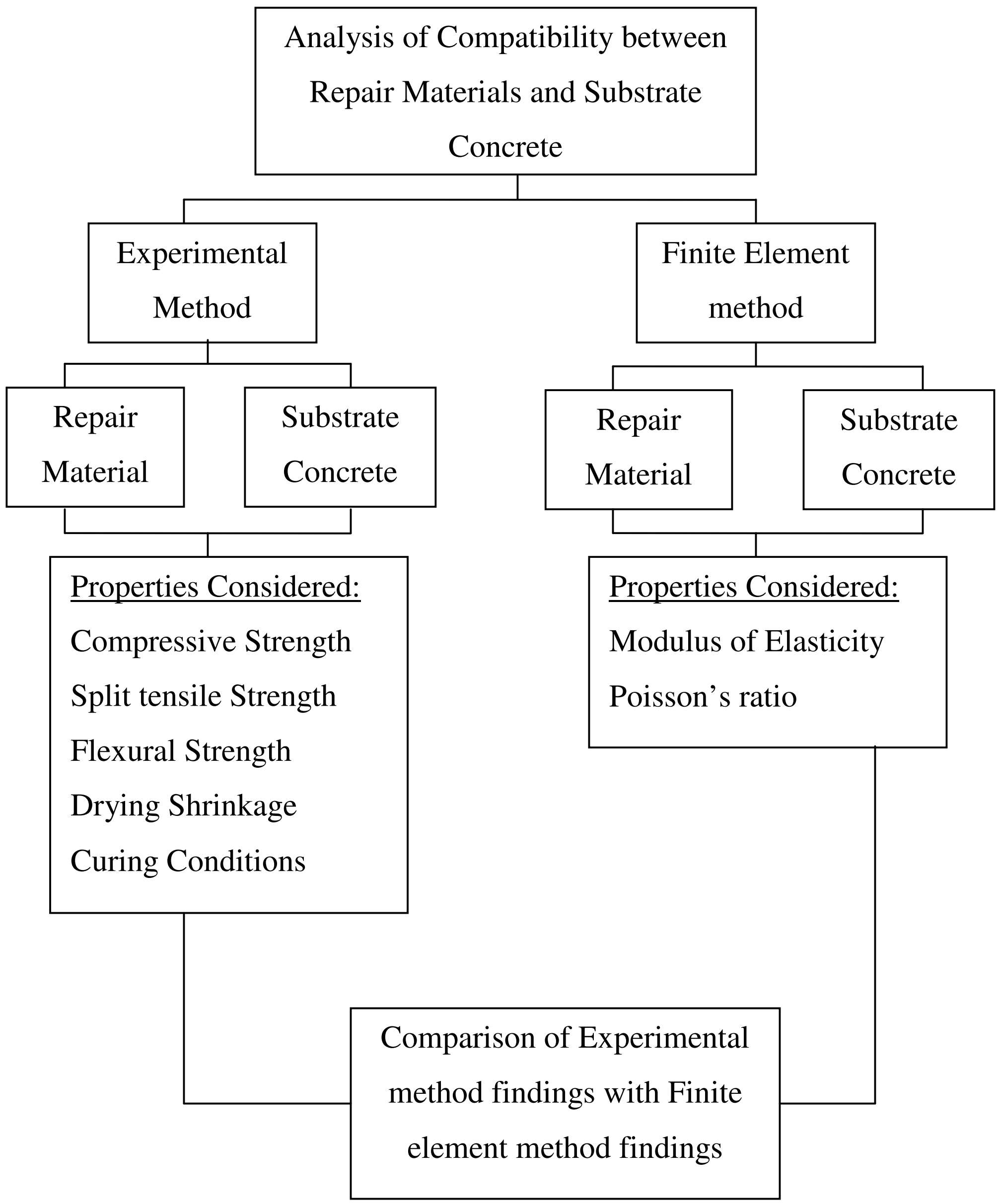


Figure 1.4 Flowchart for Analysis of Compatibility Between Repair Materials and Substrate Concrete.

Step 4 and 5, Figure 1.5 shows the material properties of the repair material considered to correlate with the compatibility between repair material and substrate concrete.

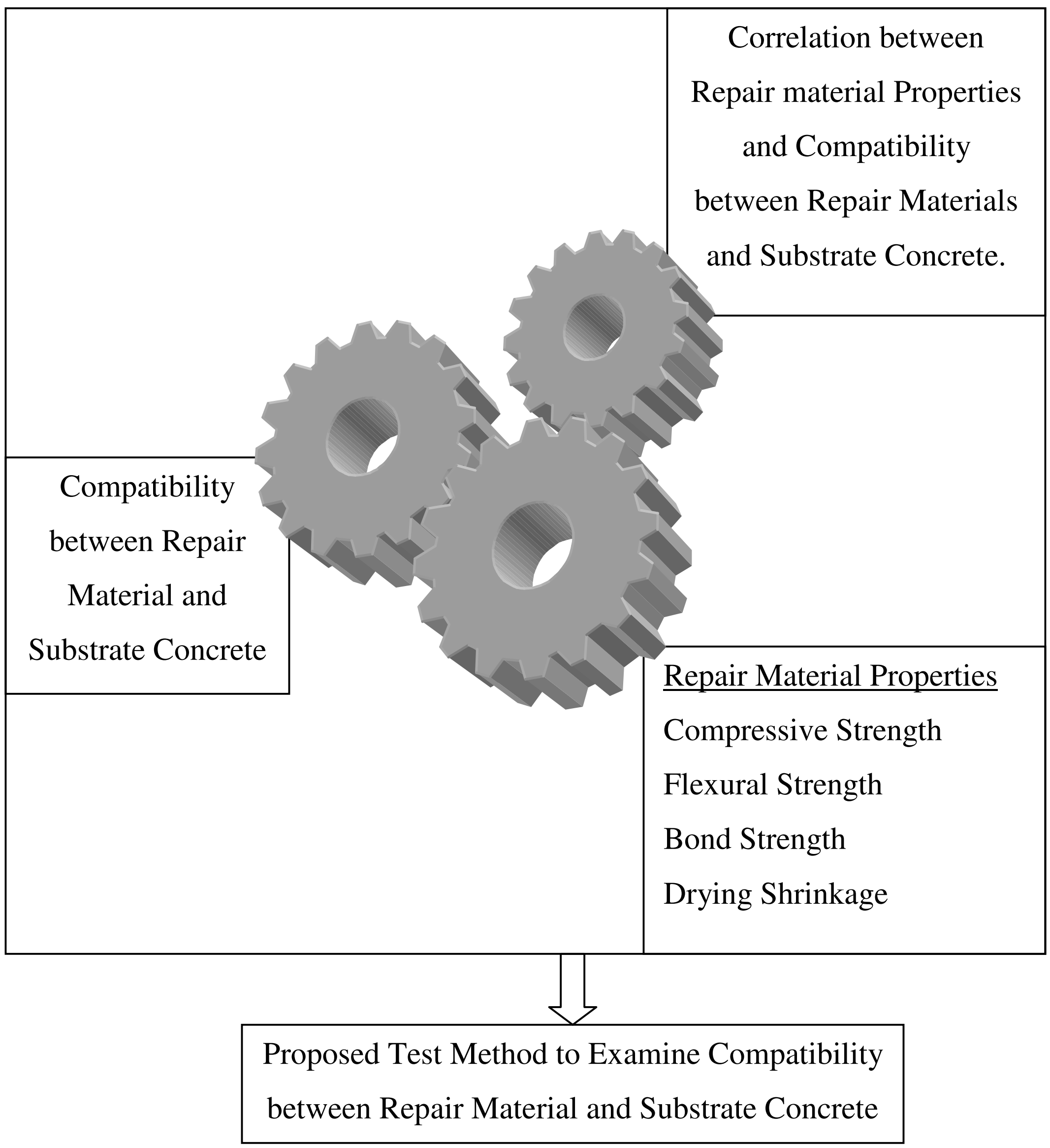


Figure 1.5 Flowchart for the Correlation Between Compatibility and Repair Material Properties

1.5. Organization of the Research Report

The work done as a part of this dissertation is divided into ten chapters. Chapter One provides background information on the research objectives and scope of this work. Chapter Two contains a literature review that provides a concise summary of the existing state of knowledge on bond strength and compatibility between repair and substrate concrete. Chapter Three provides the materials used in this research and the experimental programs conducted including mechanical and durability properties as determined. Chapter Four discusses the results found from the experimental programs. Chapter Five provides the analysis of bond strength of repair materials based on the results of the experimental program and finite element method. Chapter Six provides the investigation into the compatibility between repair and substrate concrete using a composite beam under third point loading. Chapter Seven provides the correlation of repair materials properties with compatibility of the repair and substrate materials. Chapter Eight provides a summary of this research and proposed a test method to evaluate the compatibility. Chapter Nine provides the conclusion and findings in this research. Chapter Ten provides recommendations for future scope of work.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

The primary objective of this chapter is to provide the background for the research performed in this dissertation. This chapter covers topics in which significant work has already been done, and for which findings are already available in the literature. The first section of this chapter outlines the types of repair material available in the repair of concrete industries. The second section discusses the selection process of the repair materials for durable repair. The third section outlines the material properties to be considered for compatibility between repair and substrate concrete. The fourth section outlines the material properties of concrete repair materials influencing the compatibility. The fifth section outlines the test procedures used to select repair materials, the merits and demerits of those methods. The sixth section discusses on ASTM C 882 slant shear bond strength test procedure, which is most widely used, and the shortcomings of the test procedure.

2.2. Types of Repair Materials

A wide variety of patch repair materials are now available to the industries, which can be classified into three primary groups: cementitious mortars, polymer-modified cementitious mortars, and resinous mortars (Emberson and Mays, 1990; Cusson and Mailvaganam, 1996). Table 2.1 illustrates how these groups can be further subdivided.

Table 2.1 Types of Repair materials (after Emberson and Mays, 1990)

Cementitious materials	***Polymer-Modified cementitious materials***	***Resinous materials***
Ordinary Portland Cement (OPC)	Styrene Butadiene Rubber modified	Epoxy mortar
High Alumina Cement (HAC)	Vinyl Acetate modified	Polyester mortar
		Acrylic mortar

It is essential that the engineer should have a thorough knowledge of the mechanical and physical characteristics of the available products and the existing substrate before a suitable repair material is chosen (Emberson and Mays, 1990).

2.2.1. OPC mortar or concrete as Repair Material

Ordinary Portland Cement (OPC) mortar or concrete is one of the most reliable repair materials; however it needs time for curing and gaining strength. If we consider concrete pavement repairs with OPC, the repair performed would necessitate detours or lane closures for extended periods of time (United Facilities Criteria, 2001). Such detours and closures are becoming increasingly difficult to justify in terms of user costs, delays and increased accident rates, as traffic volumes over the entire transportation network continue to increase (Sharp et al. 1997). In an attempt to reduce the time required for repairs, the construction industry has seen a significant increase in the use of rapid hardening cementitious repair materials.

2.2.2. Rapid hardening Repair Materials

Rapid-hardening repair materials are defined as those that can develop a minimum compressive strength of 20 MPa (3,000 psi) within eight hours or less (US Army Corps of Engineers, 1995). These materials used to minimize out-of-service time for repairing pavements and bridge decks. These materials include concrete made with Type III portland cement, concrete containing regulated-set Portland cement, gypsum-based concrete, magnesium phosphate concrete, and concrete containing high alumina cement (Baldwin and King, 2003).

High strength and high performance concrete is also a potential repair material for rehabilitation and repair (Zia et al. 1991; Ehlen, 1997; Sharp et al. 1997; Heath and Roesler, 1999). The possible benefits by using these materials include reduced construction times, rapid repairs, improved durability, reduced wear, and increased life of the facility. If these materials are used in the construction of a new highway the major benefit would be improved durability and a resultant increase in service life, however the benefit that holds the greatest promise is likely the shortening of closure times for repair and rehabilitation efforts with no loss in future performance (Parameswaran 2004)

The large number of commercially available repair materials with a wide variation in the mechanical properties makes the proper selection of a suitable patch repair material a daunting task (Cusson and Maivaganam, 1996). The material cost, shelf life, physical properties, workability, and performance also vary greatly among the different types of materials, and even from brand to brand within each type (Smith et al. 1991). The engineer must determine which materials are suitable for a particular environment and working conditions as different materials have varying working tolerances, such as air temperatures and surface-wetting conditions during placement, mixing quantities and times, and maximum depths of placement (Wilson et al. 1999).

Traditionally, the selection of an optimum patch material has been based on the data supplied by the manufacturers, who provide test results for relevant material properties. However, the manufacturers' data sheets provide little or no information about the long-term behavior and dimensional stability of rapid setting and high performance repair materials, probably because there is no ASTM test method to qualify these behaviors. There is also limited information available on the long-term field performance of these materials. Since relative dimensional changes, between the repair material and substrate, can cause internal stresses at the interface, particular attention should be paid to minimizing these stresses and to select materials that properly address relative dimensional behavior (Poston et al. 2001). The long-term performance of the patch repair material is a key consideration while comparing different alternatives.

2.3. Selection of Repair material

The topic of repair is more complex than the design of new structures, and the management of rehabilitation is more complex than that of new construction (Van Gemert, D., 1996). The selection of an optimum repair material is one of the critical factors that dictate the success of any repair process. Surface preparation, the method of application, construction practices, and inspection are also determining factors in the selection process (US Army Corps of Engineers, 1995). Selection of an optimum repair material with regard to cost, performance and risk is, however, not an easy task. It requires knowledge about the user expectations from the repair process, and the material behavior in the cured and uncured states in the anticipated service and exposure conditions (Emmons, 1993; Poston et al. 2001). The entities that are involved in and affected by the repair process are the agencies that implement the repair process, the users of the facility, and/or other users indirectly affected by the repair process. The agency's expectations from repair can be divided into two stages: a) during the implementation of repair, and b) after the repair is completed. During the implementation of repair, the agency's primary concern is the time required for completing the repair, since this has a direct bearing on the user costs associated with the closure of the facility. Once the repair process is complete, the primary expectation of the agency is that the repair should be durable. This is indicated by the ability of the repaired pavement to endure varying environmental, temperature and load-related changes without deteriorating.

Figure 2.1 shows a systematic approach that is required in the selection of a repair material, which accounts for all applicable parameters and their impacts on the choice between alternatives (Haas, 1978; Emmons, 1993; Cusson and Mailvaganam, 1996, Ehlen, M.A. 1997; ACPA, 1998; Hall et al. 2001).

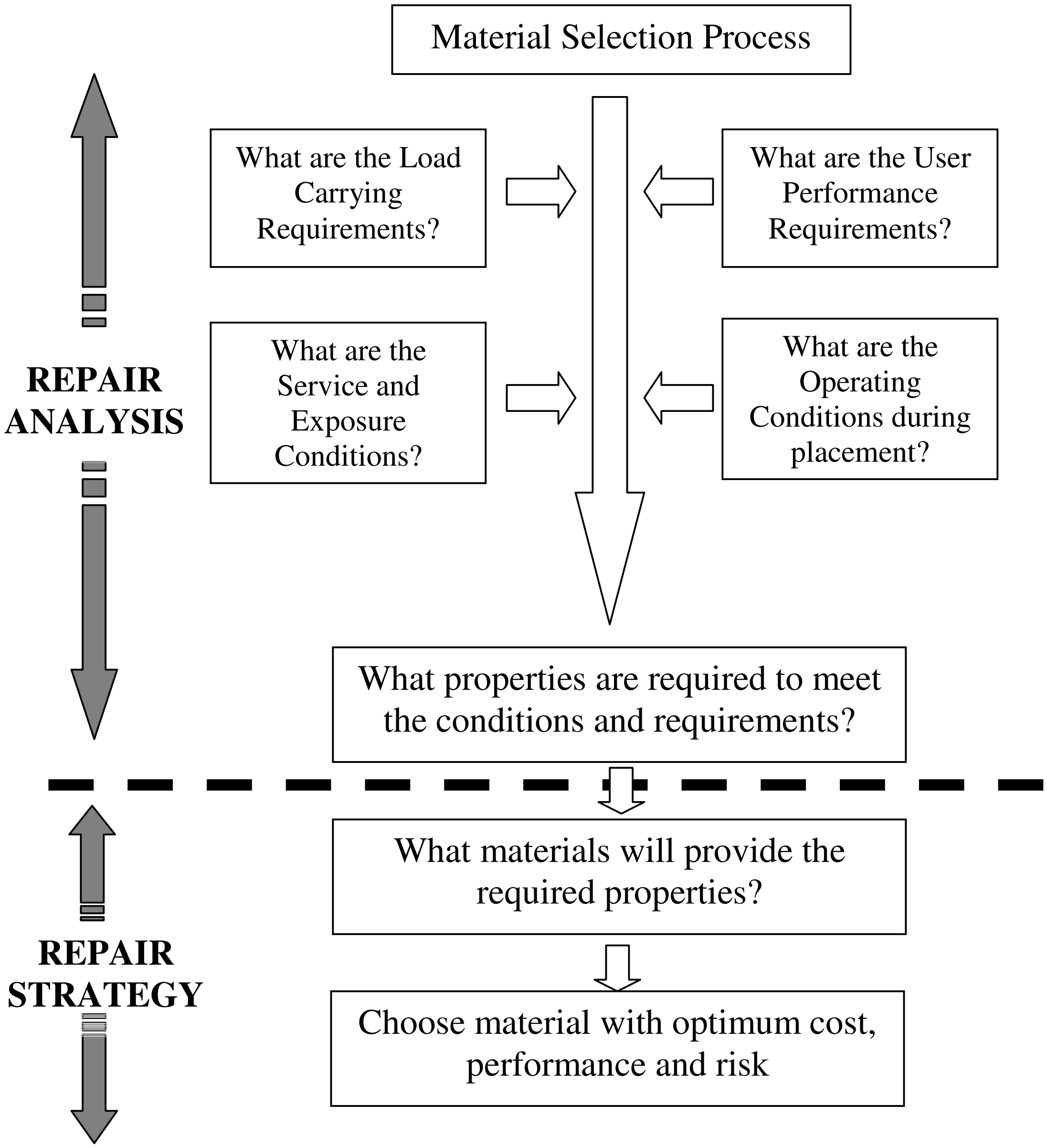


Figure 2.1 Flowchart Illustrating the Selection Process for a Repair Material (after Emmons, 1993)

2.4. Compatibility between Repair material and Substrate concrete

The compatibility of materials and sections is a complex subject with many different facets. Compatibility can be defined as a balance of physical, chemical, and electrochemical properties and dimensions between a repair material and the existing substrate that will ensure that the repair can withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over a designed period of time. The factors by which the repair materials should be selected are shown in the Figure 2.2 (Emmons et al. 1993).

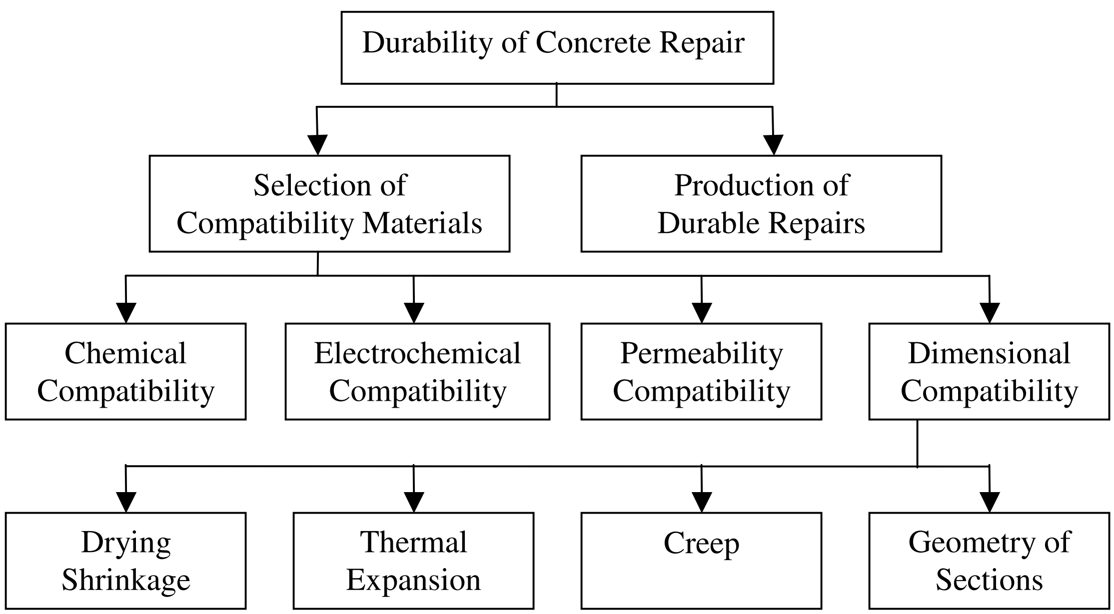


Figure 2.2 Factors Affecting Durability of Concrete Repair (after Emmons et al.1993)

Good compatibility between the repair material and the substrate ensures a repair with a limited and predictable degree of change over time, where the repair material can withstand stresses resulting from volume changes and load for a specified environment over a designated period of time without experiencing distress and deterioration throughout its intended life and purpose (Emmons, 1993; Cusson and Mailvaganam, 1996). However, since it is unlikely that a repair material will be found that behaves in exactly the same fashion as the substrate when subjected to loads, temperature and moisture changes, choosing an optimum repair material is a job of compromise (Emmons, 1993).

2.5. Factors influencing the Compatibility

To achieve durable repairs, it is necessary to consider the factors affecting the design and selection of repair systems as parts of a composite system. The factors influencing the compatibility between repair material and substrate concrete include mechanical properties such as Modulus of Elasticity, Compressive strength, Flexural strength, etc., and durability properties such as Drying Shrinkage, Freeze thaw cycles, etc.

2.5.1. Modulus of Elasticity

Low modulus materials deform more than those of high modulus under a given load. When the external load (compressive or tensile) is applied parallel to the bond line (see Figure 2.3a), materials with different elastic moduli will transfer stresses from the low modulus material (lower load-bearing effectiveness) to the high modulus material, leading to stress concentration and failure of the high modulus material (Hewlett and Hurley 1985). When the external load is applied perpendicular the bond line (see Figure 2.3 b), the difference in stiffness between both materials is less problematic if the external load is compressive. However, if the perpendicularly applied external load is tensile, mismatching elastic modulus is likely to cause adhesion failure. The higher modulus material imposes a severe constraint on the transverse contraction of the lower modulus material. High concentrated stresses can then locate in the lower modulus material very close to the interface and initiate failure. Therefore, when selecting a repair material, designer should ensure that both substrate concrete and the repair material posses similar elastic moduli (Cusson and Mailvaganam 1996).

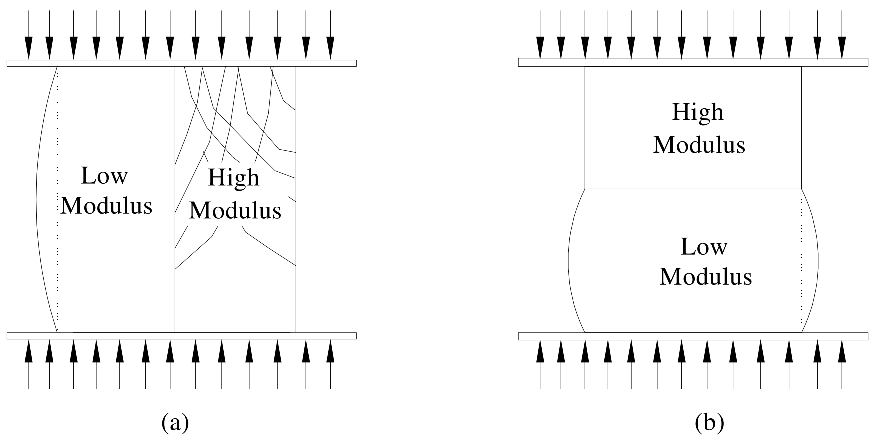


Figure 2.3 Effects of Mismatching Elastic Moduli (a) Load parallel to interface (b) Load perpendicular to interface (after Cusson and Mailvaganam 1996)

2.5.2. Poisson's Ratio

Poisson's ratio controls the magnitude of the transverse strain in relation to the strain in the direction of the applied uniaxial loading. The effect of poisson's ratio is greatest when the bond interface is perpendicular to the direction of loading and negligible when load is parallel to the interface (Emberson and Mays 1990). Bonded materials with mismatched poisson's ratios can generate differential transverse strains at the bond line if the interface is perpendicular to loading, causing cracking at the interface.

For this reason , it is important that both the substrate concrete and the repair material have similar poisson's ratio (Cusson and Mailvaganam 1996).

2.5.3. Tensile Strength

A tensile force can be generated in a repair material by a combination of external loading (impact, sustained and cyclic), volume changes (shrinkage, creep, and temperature and humidity variations) and mismatches in the properties of the repair material and the substrate concrete. When any of these forces produce a tensile stress in excess of the repair material's tensile capacity, failure of the material can be expected in the form of tensile cracks, spalling or debonding. Thus, tensile strength is an important property to consider when selecting an appropriate material for a repair project (Cusson and Mailvaganam 1996).

2.5.4. Porosity and Resistivity

The Porosity and reisistivity of repair material is important when durability of the repair is concern. Repair materials that are dense, impermeable, highly resistivity or nonconductive have a tendency for the repair area to become isolated from adjacent undamaged areas. Consequently, there is a large porosity or chloride content differential between the patched area and the rest of the concrete which in turn, causes the current from the resultant corrosion to become concentrated in a restricted area. The rate of steel corrosion may then be accelerated, causing premature failure in either the patch or the adjoining concrete. Therefore, when selecting a repair, it is important to ensure that both the substrate concrete and the repair material possess similar porosities or densities (Gu et al.1994).

2.5.5. Chemical Resistivity

The reactivity of the patching material with steel reinforcement and other embedded metals, with the aggregate in the concrete, or with specific sealers or protective covering applied over the patch is a concern in selecting repair materials. Repair materials with low or moderate pH provide little protection to concrete while high alkaline material may attack potentially reactive aggregates in the concrete causing cracks and debonding of the repair (Kosednar and Mailvaganam 2005).

2.5.6. Thermal Expansion Coefficient

The coefficient of thermal expansion is a measure of the change of length in a material when it is subjected to a change in temperature. When two material (repair material and substrate) of different coefficient of thermal expansion are joined together and subjected to significant temperature changes, stresses are generated in the composite material. These stresses may cause failure at the interface or in the lower strength material. This particularly evident in meat processing plants where floors are coated with epoxy toping (which has a higher thermal expansion coefficient) to shear off at the interface. Unless the temperature change is expected to be very small, the repair material should possess a thermal expansion coefficient similar to that of the substrate concrete (Cusson and Mailvaganam 1996).

2.5.7. Shrinkage Strain

In cement-based materials, most of the shrinkage occurs when the cement paste dries out after setting and hardening. In resin-based materials, shrinkage is a result of cooling following the exothermic reaction, particularly, for repair patches where patch thickness exceed 0.59in (15mm). When shrinkage is restrained, permanent tensile stresses develop in the concrete repair material that result in the formation of tensile cracks in the concrete repair material itself, or in delamination at the interface of the repair material and the substrate. Since most repair materials are applied to an older substrate concrete that has negligible shrinkage, repair materials with very low shrinkage potential should be chosen to minimize the compatibility problems between repair material and substrate concrete (Hewlett and Hurley 1985).

2.5.8. Creep Coefficient

Creep is the continuous deformation of a member subjected to a sustained applied load. It can result in reduced load bearing effectiveness in the repair material and also result in load transfer from the repair material to the substrate concrete, or to a non structural repair loaded in compression, the repair material must possess very low creep potential. On the other hand, in the case of repair patches loaded in tension, creep can be beneficial, as it can reduce or cancel the adverse effect of shrinkage in the repair material (Cusson and Mailvaganam 1996).

2.6. Test Methods to Select Repair Materials

The following test methods were used previously to assess the performance of the repair materials.

2.6.1. Compressive Strength

Although compressive strength is not an important property in many repair applications, because the repair in most cases needs in the tension zone of the structure, compressive strength has become the singular property always reported for a concrete material (Poston et al. 2001). However, it is generally accepted that the material used should have strength properties similar or better than those of substrate concrete (Cabrera and Al-Hasan 1997). If the repair material is a mortar then ASTM C 109 standard practice was used. For deeper repair, coarse aggregate was used with the repair material and ASTM C 39 standard practice was used to measure the compressive strength.

2.6.2. Flexural Strength

Flexural strengths of repair materials were measured using ASTM C 78 standard practice to investigate the composite beam behavior with repair material and substrate concrete.

2.6.3. Modulus of Elasticity and Poisson’s ratio

For modulus of elasticity and Poisson’s ratio ASTM C 469 is used. The specimens were 3 x 6 in cylinders in place of 6 x 12in. Because, smaller sized aggregate 3/8 in or less is used as the coarse fraction. Because of the cost of the prepackaged materials, the volume required in 6 x 12in can make the strength testing expensive (Cabrera and Al-Hasan 1997).

2.6.4. Coefficient of Thermal Expansion

The coefficient of thermal expansions is an important property while the concrete repair is exposed to fluctuating temperatures. The tests were conducted according to ASTM C 531.

2.6.5. Restrained Shrinkage by SPS Plate Test

The SPS plate test for restrained shrinkage was conducted on specimen a 2 in x 4 in x 52 in dimension repair material. The repair material was cast against a thin steel plate on the bottom. The plate had a layer of epoxy and was impregnated with a sand grit applied to improve bond to the repair material. The test involved the measurement of upward tip deflection (curling) at the free end (see Figure 2.4) of the specimen at three locations over time under standard laboratory condition (Poston et al. 2000).

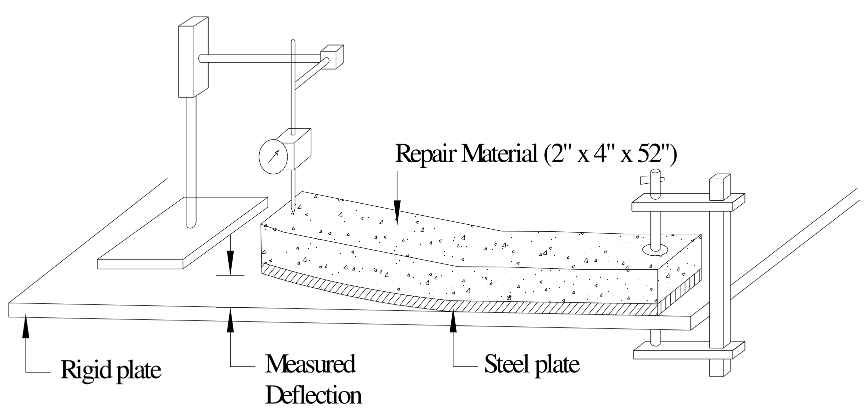


Figure 2.4 SPS Plate Test for Restrained Shrinkage of Repair Materials
(after Poston et al. 2000)

2.6.6. Restrained Shrinkage by German Angle Test

The German angle test consisted of filling a steel angle with the repair material. The angle was thoroughly cleaned with degreaser. An epoxy bonding agent was then applied to the angle. The specimen were monitored under standard laboratory conditions for cracking, with records kept of time to cracking, number of cracks, and average width of cracks as shown in the Figure 2.5 (Poston et al. 2001)

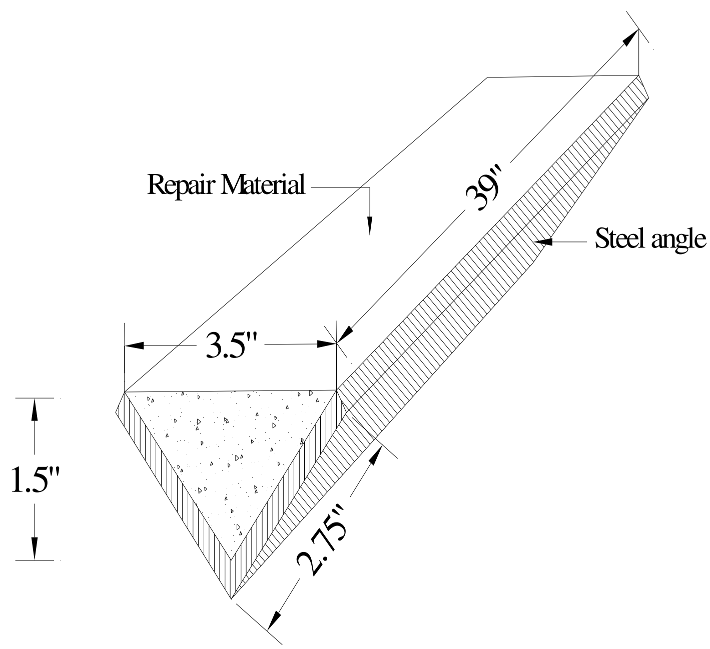


Figure 2.5 German Angle Test for Restrained Shrinkage of Repair Materials
(after Poston et al. 2001)

2.6.7. Restrained Shrinkage by Ring Test

In the ring test repair materials were cast around a 1-in. thick steel pipe of 2-in. height. The material was allowed to cure in the mold for 24 h and then cured according to manufacturer's recommendations. The rings were monitored daily under standard laboratory condition for evidence of cracking. The day that cracking was first observed was recorded. Periodically thereafter, each of the cracks that had formed was measured for width at three locations along the crack height and recorded Figure 2.6 (Shah et al.1992).

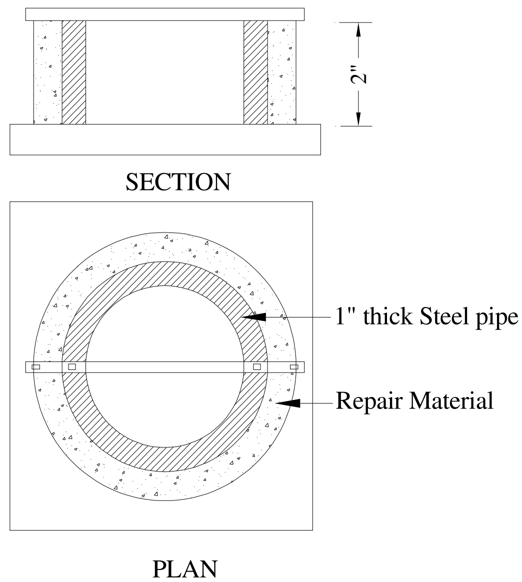


Figure 2.6 Ring Test for Restrained Shrinkage of Repair Materials
(after Shah et al.1992)

2.6.9. Third Point Loading Flexure Test

This test was conducted for compatibility between polymer composite and substrate concrete. The principle of the test consists of applying the polymer composites to a recess made on bottom of a prismatic concrete specimen as shown in Figure 2.7 and subjecting the specimen to a third point bending strength test, similar to ASTM C 78. The quality of the concrete substrate specimen was 7250 psi at 28 days. The concrete was made from aggregate having a maximum grain size of 2/3 in. During third point loading test, the repair material filled side of the specimen was placed on the bottom (tension side of the specimen) of the specimen as shown in the Figure 2.7. The repair materials were assessed compatible or incompatible with the substrate concrete by the mode of failures.

If the failure passes through repair material and substrate at the middle third of the beam, then it is a compatible failure or else the repair material is incompatible with the substrate concrete, as shown in the Figure 2.7 (Czarneck et al. 1999).

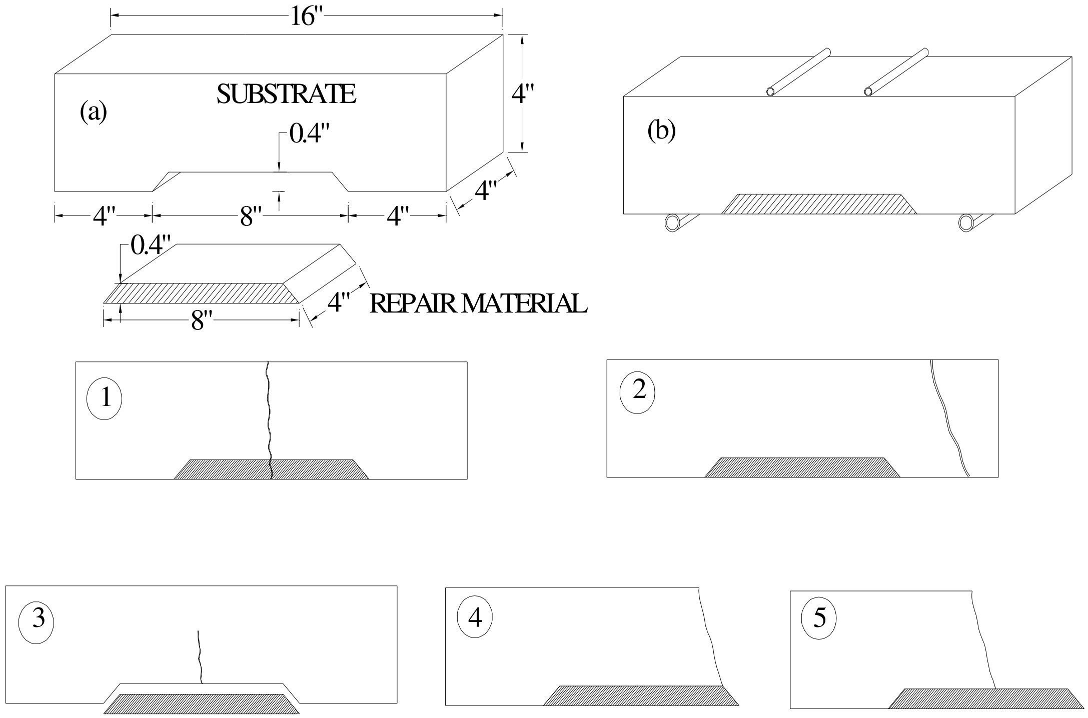


Figure 2.7 Compatibility Test (after Czarneck et al.1999)
Compatibility evaluation:1,2-compatibility; 3,4,5-incompatibility
(a) Specimen arrangement; (b) Third point loading beam test (after Czarneck et al 1999)

2.6.10. Bond Strength by Pull-off Test

In this test a core bit is drilled through the repair into the substrate concrete to isolate a partial core, as shown in the Figure 2.8, metal dolly is glued to the end of the core and pulled by a device that reacts against the surface surrounding the core. The tensile force is transmitted to the interface between repair material and concrete and the tensile stress is calculated as the bond strength of the repair material. It has been shown that the core pull off test is a good technique provided that appropriate precautions are taken to minimize the influence of repair and substrate properties (Robins and Austin 1995). More specifically, the technique is sensitive to:

(a) eccentricity of loading – a feature of all direct tension tests that results from the difficulty in coring and pulling axially and perpendicular to the bond plane

(b) coring depth into the substrate – stress concentration will occur at the base of the core cut which, if too close to the bond plane, can reduce the pull-off load.

(c) Dolly stiffness – non-uniform stresses occur in the repair material adjacent to the stiffer metal dolly which again, if too close to the bond plane (i.e. a thin overly), will reduce the pull-off load

(d) Material mismatch – for example, repair materials with significantly lower stiffness than substrate will experience a stress concentration at the periphery. Differential shrinkage and thermal movements can also cause stress concentration, which will reduce the pull-off load at failure.

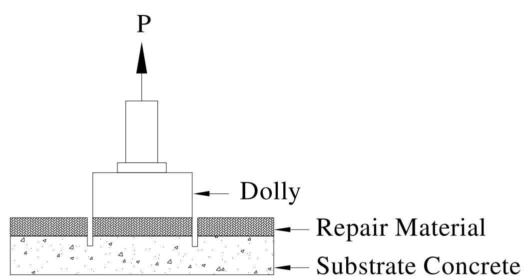


Figure 2.8 Pull off Tester

2.6.11. Bond Strength by Split Tensile Test

Split tensile test is an indirect tension test of homogeneous cylindrical specimen. This test is also used for composite cylinders, constructed with one-half concrete and other-half repair material. The bond strength between the substrate concrete and the repair material was determined as the splitting strength of the composite cylinder (Momayez et al.2004).

2.7. Shortcomings in the Slant Shear Bond Strength

Bond between repair and substrate is usually a weak link in a repaired structure, and the compatibility between repair and substrate materials is fully dependent on the bond strength of the repair materials. The bond strength mainly depends on adhesion in interface, friction, aggregate interlock, and time-dependent factors. Each of these main factors, in turn, depends on other variables. Adhesion to interface depends on bonding agent, material compaction, cleanness and moisture content of repair surface, specimen age, and roughness of interface surface. Friction and aggregate interlock on interface depend on parameters, such as aggregate size, aggregate shape, and surface preparation. In addition to the above factors, the measured bond strength is highly dependent on the test method used. Size and geometry of specimen and the state of stress on the contact surface are quite dependent on the chosen test method (Momayez et al. 2004). ASTM C928 is the most widely used standard specification for Packaged, Dry, and Rapid-Hardening Cementitious Materials for Concrete Repairs. This specification includes ASTM C882 test method for slant shear to evaluate the bond strength of cementitious repair materials. This test method puts the bond interface between repair material and substrate mortar into a combined state of compression and shear, first appeared in the form of the Arizona slant shear test (Kreigh, J.D 1976). The repair material is bonded to a substrate mortar specimen on a slant elliptical plane inclined at 30° angle from vertical to form a 3-in. x 6-in (76mm x 152 mm) composite cylinder as shown in Figure 2.9.

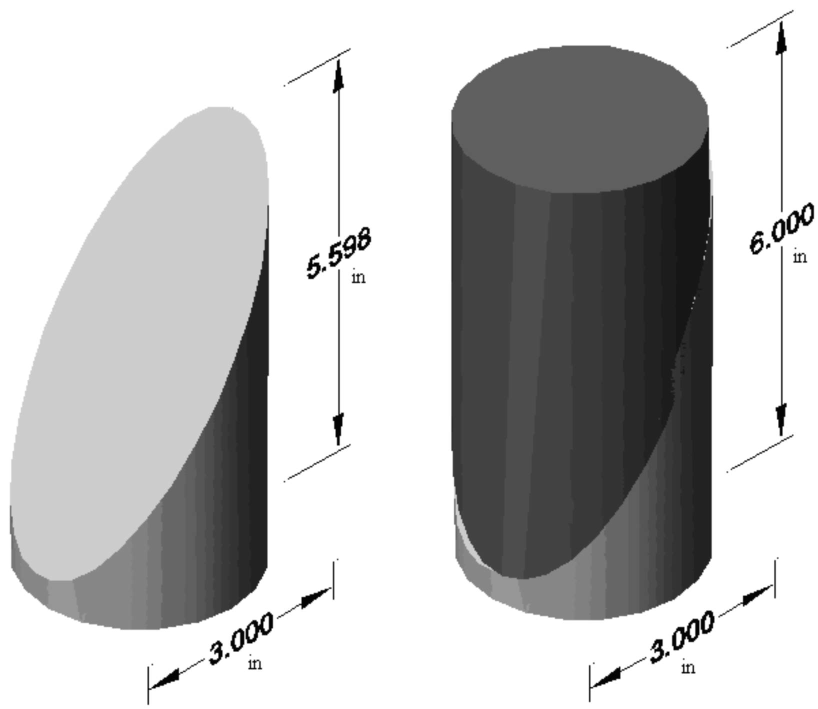


Figure 2.9 Substrate and Composite Section for Slant Shear Bond-Strength Test

Before the repair material is bonded to the substrate mortar, the slant surface of the substrate mortar specimen is prepared by sandblasting and dry brushing. The test is performed by determining the compressive load required to fail the composite cylinder and the bond strength is calculated as [Max Load]/ [Area of Slant Surface], even though the failure does not occur on the slant surface or interface. The test is widely used by manufacturers and specifiers to characterise repair products, but the test has some serious shortcomings (Austin et al. 1999). Failure is crucially dependent on the angle of the plane that is fixed in the standard test, precluding the possibility of obtaining a bond failure on a different plane, where there may be a more critical combination of compressive and shear stresses. The test is sensitive to differences in elastic modulus of the repair and substrate materials that can cause stress concentrations. Austin et al. came up with an equation 1 from the basic shear failure from Coulomb theory.

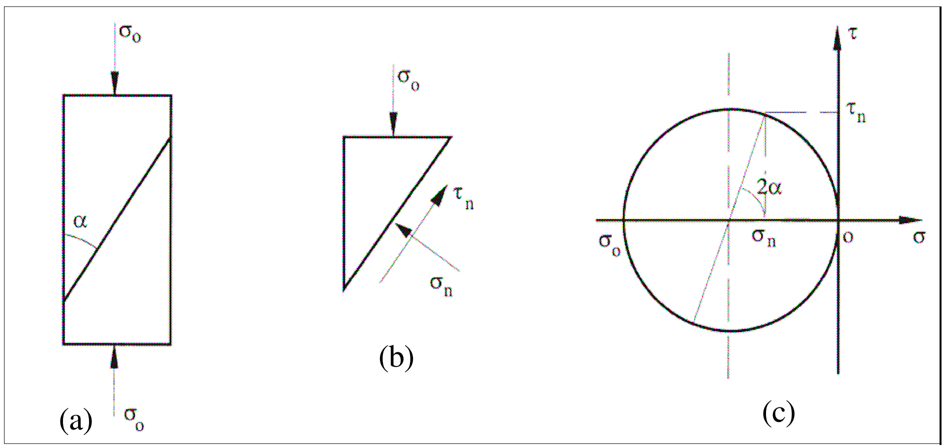


Figure 2.10 Slant Shear Configuration and Mohr Circle (after Austin et al. 1999)

$$\tau_{Critical} = c(1+\sin\phi)$$
$$\alpha_{Critical} = 45 - \frac{\phi}{2} \qquad (1)$$

Where

$\tau_{critical}$ = Shear stress on the bond interface

c = Adhesion Strength

φ = Internal friction angle

$\alpha_{critical}$ = Critical bond angle

The critical bond angle and the minimum bond strength are dependent upon the internal friction angle φ, which depends on the surface roughness. Coefficients of friction have been determined from several researchers': 0.7 for smooth sand blasted, 1.1 and 1.4 for rough surfaces (Frank, L. 1986). If values for coefficient of friction of 0.75, 1.0, and 1.25 for smooth, medium rough and rough surfaces are adopted, the critical bond angles corresponding to smooth, medium rough and rough surfaces are 27^0, 23^0, and 19^0 respectively (Austin et al. 1999). While, the slant shear surface is fixed at 30^0 to the vertical for all conditions. A few bond failures occur on the slant surface; most of the failure occur on the weaker material, either substrate or repair material, close to the compressive strength of the materials, indicating that a limiting material strength (rather than bond strength) initiated the failure (Robins et al. 1994).

CHAPTER THREE
MATERIALS AND EXPERIMENTAL PROGRAM

3.1. Materials for Research

In this Research eight pavements and bridge decks rapid setting cementitious repair materials as approved by the South Carolina Department of Transportation were chosen. The precise composition of these repair materials is proprietary and therefore unknown. However, these materials have wide range in their mechanical and durability properties. As with most repair materials, specific instructions provided by the manufacturer were followed in preparation of a batch of the repair material for casting the test specimens. Table 3.1 shows the type of repair materials used and manufacturer's specified water to repair material ratio.

Table 3.1. Selected Repair Materials

ID[†]	Repair Materials	W/RM*	Manufacturer's Description
A	BONSAL Rapid Patch-VR	0.123	Meets the Requirements of ASTM C 928 for Packaged, Dry, Rapid-Hardening cementitious Materials for Concrete Repairs
B	Emaco T415	0.076	One-component high-performance cementitious product. Meets ASTM C 928 specification
C	Futura 15	0.109	One component, cementitious, very rapid-hardening structural repair mortar designed for horizontal application
D	Emaco S88 CI	0.130	One-component rheoplastic, shrinkage-compensated, fiber-reinforced product that contains an integral corrosion inhibitor. It contains silica fume to offer high strength and superior performance for structural concrete repairs
E	BONSAL Magna 100	0.084	Magnesium phosphate cement and sand based concrete repair material. Meets ASTM C 928
F	BONSAL Fast Set Cement Mix	0.166	Polymer modified, rapid setting hydraulic cement repair mortar. Meets ASTM C 928
G	QUIKRETE FastSet Repair Mortar	0.191	Meets the requirements of ASTM C928 Type R2 with reduced flow for vertical and overhead applications.
H	QUIKRETE FastSet Cement	0.374	Specially blended fast-setting cement designed for new construction or to make durable repairs to concrete. QUIKRETE FastSet Cement can be used to formulate products complying with the requirements of ASTM C928 Type R2 or R3.

[†] Material Identification in this Research
* Water to Repair material ratio

In addition to the repair materials, ASTM Type-I Portland cement was used along with river sand in preparing the substrate mortar specimens. The mortar was proportioned to have a cement-to-sand mass ratio of 1:2.5, with a water-to-cement ratio of 0.45. And, coarse aggregate of 3/8- in. was used for the substrate concrete. The mix proportion of the concrete is as shown in Table 3.2

Table 3.2 Substrate concrete proportions, per yd^3

Items	Quantity
Water-cement ratio, based on SSD aggregate	0.40
Mix water	290 lb
ASTM Type-I Portland cement	611 lb
Coarse aggregate (oven dry)	1800 lb
Fine aggregate (oven dry)	1270 lb
High range water reducer	12 oz/cwt

3.2. Mechanical and durability Properties

3.2.1. Flow of Repair materials

Typically, the repair materials are the cementitious mortar. Therefore, the flow of the repair materials was determined using flow table of mortar as per ASTM C230 standard practice. Flow was measured immediately after mixing, within 5 minutes from the time of addition of water into the mix, because of the rapid setting of the repair materials.

3.2.2. Setting Time

Setting time of the repair materials were measured using Vicat needle as per modified ASTM C191 standard practice of method A (manually operated). The initial time of setting was determined as the elapsed time required to achieve a penetration of 1-in. and the final setting as the total elapsed time when the needle does not sink visibly into the paste. The frequency of penetration of the needle was every minute from the repair material poured inside the container, except repair material D.

Figure 3.1 Compressive Strength Test (ASTM C109)

3.2.3. Compressive Strength

The compressive strength of the repair materials were determined using 2-in cube as per the ASTM C 109 standard practice, since the repair materials are primarily mortars. The compressive strengths of substrate concrete were determined using 3-in x 6-in cylinder as per ASTM C39. The cubes of the repair materials were tested in compression at 3hrs, 8hrs, 24hrs, 14 days, and 28 days. The cylinders of the substrate concrete were tested at 35 days and 63 days, corresponding to the day of casting and 28 days of repair materials, respectively. Additional cubes and cylinders of repair materials and substrate concrete were tested for their compressive strength alongside the composite sections, from the same batch, to study the compressive strength difference on the compatibility of the repair materials.

3.2.4. Split Tensile Strength

The split tensile strength of the substrate mortars and the repair materials was determined on 3-in. x 6-in. cylinders as per the ASTM C 496 test procedure. The split tensile strength of the repair materials was determined at 1hr, 8 hrs, 24 hrs, 14 days, and 28 days. While, the split tensile strength of the substrate mortar was determined at 1 day and 28 days. Additional cylinders of the substrate mortar were tested for their split tensile strength alongside the slant shear tests conducted on the composite cylinders for determining the bond strength of the repair material.

Figure 3.2 Split Tensile Strength Test (ASTM C596)

3.2.5. Flexural Strength

The flexural strength was determined using the third point loading beam method. For the repair materials, which are primarily mortars (consisting of aggregate smaller than #4), prisms of 6-in length and 1-in x 1-in cross-sectional area were used. While, for substrate concrete (consisting of 3/8-in maximum size aggregate) prisms of 12-in length and 3-in x 3-in cross-sectional area were used. The flexural strength of the substrate concrete was tested at 63 days, corresponding to 28 days test of repair materials.

3.2.6. Drying Shrinkage

The drying shrinkage of repair materials was measured on 12-in length and 1-in x 1-in cross sectional area of prismatic section as per ASTM C157 standard practice. The specimens were moist cured for 3 days prior to testing. The readings were taken at 7 days, 14 days, 21 days and 28 days, and drying shrinkage percentage was measured with reference reading of at 4 days after the moist curing (see Figure 3.3).

Figure 3.3 Comparator Readings

3.2.7. Freeze-thaw Resistance

The freeze-thaw of repair materials was measured on 12-in length and 3-in x 3-in cross sectional area of prismatic section as per ASTM C666 standard practice. The specimens were moist cured for 14 days prior to testing. Length change and dynamic modulus were monitored at every 30 cycles until 300 cycles. Durability factor and final length change were measure at the end of 300 cycles.

3.2.8. Rapid Chloride Permeability

The rapid chloride permeability was measured on water saturated 2-in thick and 4-in diameter repair materials subjected to a 60 V applied DC voltage for 6 hours as per ASTM C666 standard practice. The specimens were moist cured for 28 days prior to testing. The total charge that passed through the specimen in Coulomb was recorded at the end of 6 hours.

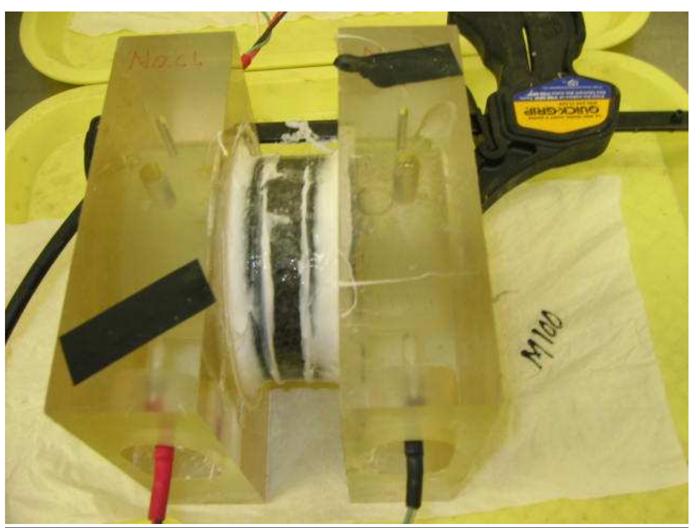


Figure 3.4 Chloride Permeability Tests of the Repair materials

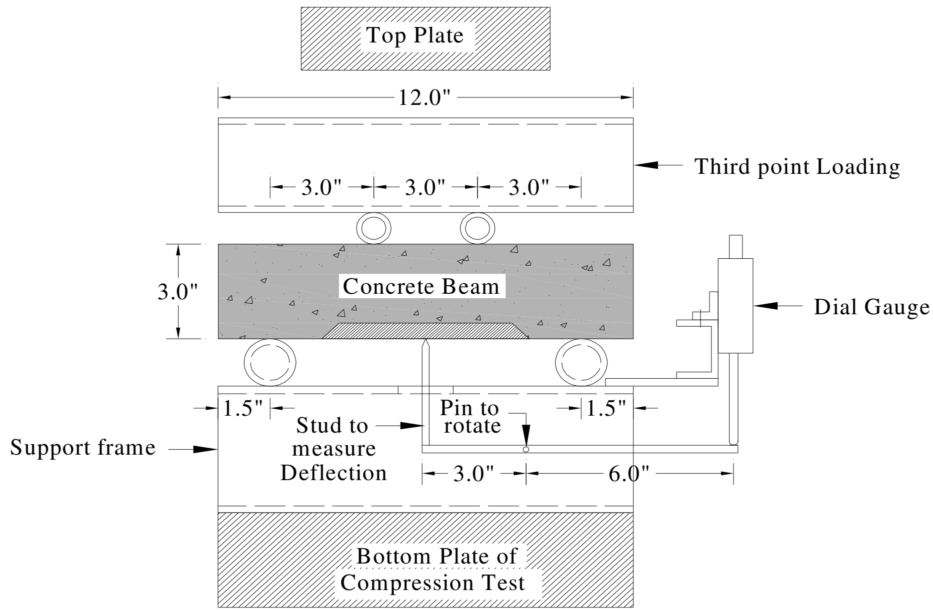
3.2.9. Slant Shear Bond Strength:

The bond strength of the repair materials is determined using the standard ASTM C 882 test procedure. In this test procedure, the repair material is bonded to a substrate mortar specimen on a slant elliptical plane inclined at 30° angle from vertical to form a 3-in. x 6-in composite cylinder (see Figure 2.9 and Figure 3.5). Before the repair material is bonded to the substrate mortar, the slant surface of the substrate mortar specimen is prepared by sandblasting and dry brushing. The test is performed by determining the compressive load required to fail the composite cylinder and the bond strength is calculated as [Max Load]/ [Area of Slant Surface]. In this study, two classes of bond strength – Minimum bond strength (as calculated per ASTM C 882) and Actual Bond Strength – are recognized for sake of clarifying the mode of failure. If the failure occurred on the slant surface, the actual bond strength is same as the minimum bond strength. However, if the failure surface is not on the interface, the bond strength as per the ASTM C 882 calculation represents minimum bond strength. In these tests, the substrate mortar used in evaluating the bond strength is required to have a minimum compressive strength of 4500 psi at 28 days of age as per ASTM C 882 test method.

Figure 3.5 Slant Shear Test (ASTM C882)

3.2.10. Third Point Loading Composite Beam Test

In this test method, concrete prisms 12-in. in length with a cross-section of 3in x 3in was cast as per standard ASTM C 78 test procedure. In this test procedure the span length of the prism should be at least three times it's depth as shown in Figure 3.6a. The load is applied through two points that are located at one-third of the span length from each support. As a result, the maximum stress is induced in the middle-third of the prism. The flexural strength determined from this procedure is referred to as Modulus of Rupture. The composite prism for evaluating the compatibility of repair material with substrate concrete was fabricated to the same dimensions as the control prism, with the exception that a wide-mouthed notch 6 in (length) x 3in (width) x ½ in (thick) was cast into the bottom of the composite prism using a 3-dimensional inset (see Figure 3.6a). After de-molding, the prisms were moist cured for 28 days, and then the wide-mouthed notch areas were textured using sand blasting and dry brushing. The rough surface textured substrate specimens were air-dry cured for 7 days before patching the notched area with the repair materials. The composite sections were de-molded next day and cured in three different curing conditions for 28 days. After 28 days, the composite sections were tested in third point loading beam test, as per ASTM C78 test procedure. Also, at the time of testing for flexural strength, the deflections in the prisms at the center were measured to examine the mode of failure with the deformation. The details of the curing methods are provided in the effect of different curing methods on compatibility (presented in chapter six)



(a) Skeletal View

(b) Front View

Figure 3.6 Measurement of Deflection in the Composite Beam

CHAPTER FOUR
RESULTS

4.1. Mechanical Properties of the materials

4.1.1. Flow of Repair Material

Table 4.1 shows the flow of the repair materials. An increase in the flow of mortar at the time of use is beneficial for the repair. It provides greater control over the repair material mortar for laying on the substrate concrete. This is because some of the repair materials set within 10 minutes from the time of mixing.

Table 4.1 Flow Repair Materials

RM*	A	B	C	D	E	F	G	H
Flow (%)	>150	113	113	63	113	>150	63	97.5

* Repair Materials

113% Flow of Repair Material
Figure 4.1 Flow of Repair Material

4.1.2. Setting time

Figure 4.2 shows the initial setting time and final setting time of the repair materials. It can be observed all the repair materials except repair material D, set within one hour from mixing.

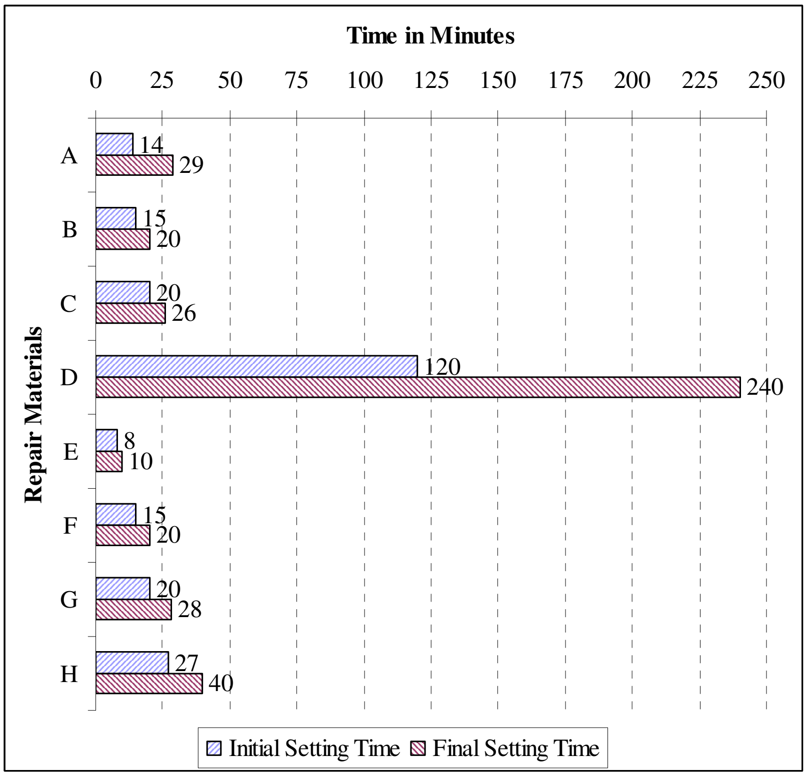


Figure 4.2 Setting Time of the Repair Materials

4.1.3. Compressive Strength

Table 4.2 shows the compressive strength of the repair material. These values are the average of the compressive strengths of three cubes as shown in the appendix from Table A25 to A28. All the compressive strengths found increasing from 1hr to 28days except the repair material E, which showed lower compressive strength at 14days and 28days. Further investigation revealed that the repair material E looses its strength in moist curing. Table 4.3 shows the compressive strength of the repair material in 7 days moist curing and in air-dry cure conditions.

Table 4.2 Compressive Strength of Repair materials in Moist Cure Condition

	Compressive Strength in psi						
	1-hr	3-hr	8-hr	24-hr	2-days	14-days	28-days
A	2945	4984	5797	7598	8234	9232	9419
B	1510	3098	4398	5253	7389	9201	9165
C	3041	4338	5495	5958	5817	8599	9653
D	-	-	972	3252	5294	11594	11729
E	5278	5568	6468	6927	7220	4326	4431
F	1561	2291	3362	4354	5370	7129	8000
G	457	2959	3794	5590	5696	6184	6320
H	191	711	3880	5143	5494	6307	6614

Table 4.3 Compressive strength of Repair Materials in Different Curing Conditions

	Compressive Strength in psi					
	Moist Cure (7-days)			Air-dry Cure		
	14-days	21-days	28-days	14-days	21-days	28-days
A	10273	10892	11666	9376	10230	11151
B	9984	10438	11791	9392	9342	9558
C	8239	9316	9830	8996	9025	9653
D	9068	9823	10409	8378	8446	8761
E	5480	6052	8069	5221	5955	8155
F	7886	8110	8362	5462	5981	6830
G	7920	7994	8408	6168	6278	6465
H	4917	6301	7088	4810	5379	5845

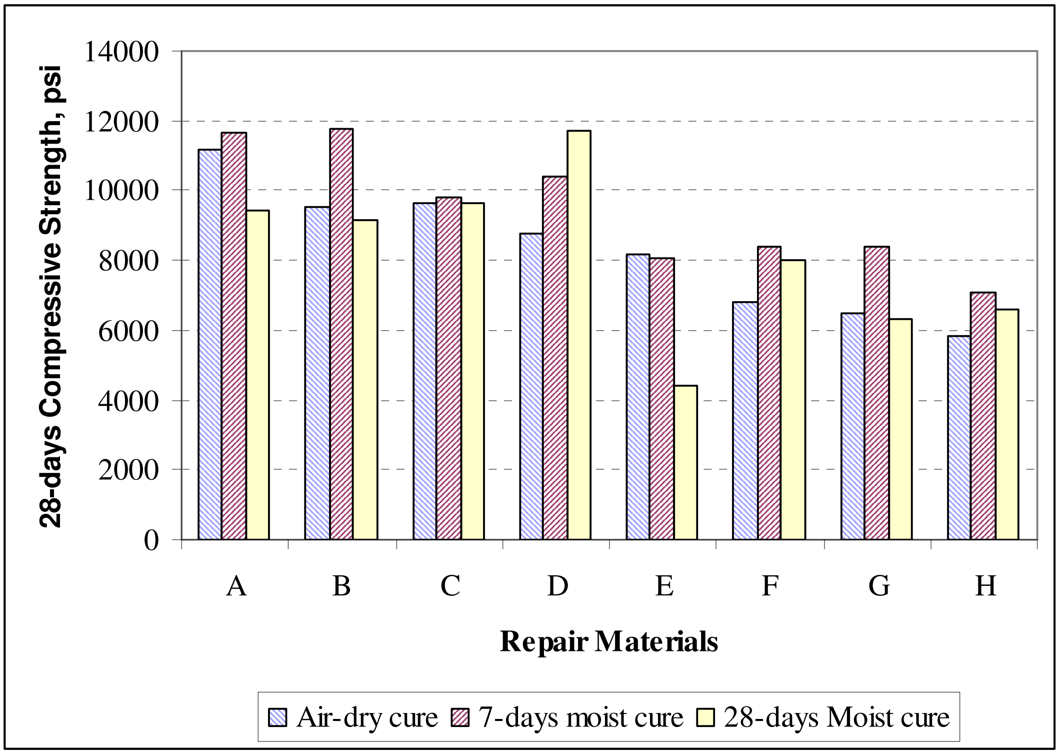


Figure 4.3 Compressive Strength of the Repair Materials at 28 days in Difference Curing Conditions

Figure 4.3 shows the difference in compressive strength at 28days in different curing. It can be observed from the Figure 4.3 that the repair material C does not change much in compressive strength in different curing conditions. While, the repair materials D, F, and H gain strength due to moist curing. The difference of these strength influences the bond strength and hence compatibility between the repair materials and substrate concrete, which are discussed in chapter five and six.

4.1.4. Split Tensile Strength

Table 4.4 shows the split tension of the repair materials. These values are average of three specimens as shown in the Appendix from Table A29 to A32. One hour split tensile strength of the Repair material D was not recorded as the final setting time of the repair material is 4 hours. Repair Materials G and H recorded very low tensile strength at 1 hour.

Table 4.4 Split Tensile Strength of the Repair Materials

	Split Tension in psi				
	1-hr	8-hrs	24-hrs	14-days	28-days
A	197	489	704	763	768
B	190	329	516	722	786
C	342	711	660	790	880
D	-	504	774	902	1033
E	313	334	399	365	415
F	279	463	557	701	787
G	19	395	382	796	712
H	12	396	456	554	608

4.1.5. Flexural Strength

Figure 4.4 shows the flexural strength of the repair material in three different curing conditions. These values are the average of three specimens as shown in the Appendix from Table A19 to A21. It can be observed repair materials E, F, and G reduce flexural strength in alternate moist and air dry curing condition. Repair material B, D and E showed higher flexural strength in air dry cure than in moist cure condition. These variations in flexural strength influence the compatibility, which is discussed in chapter six.

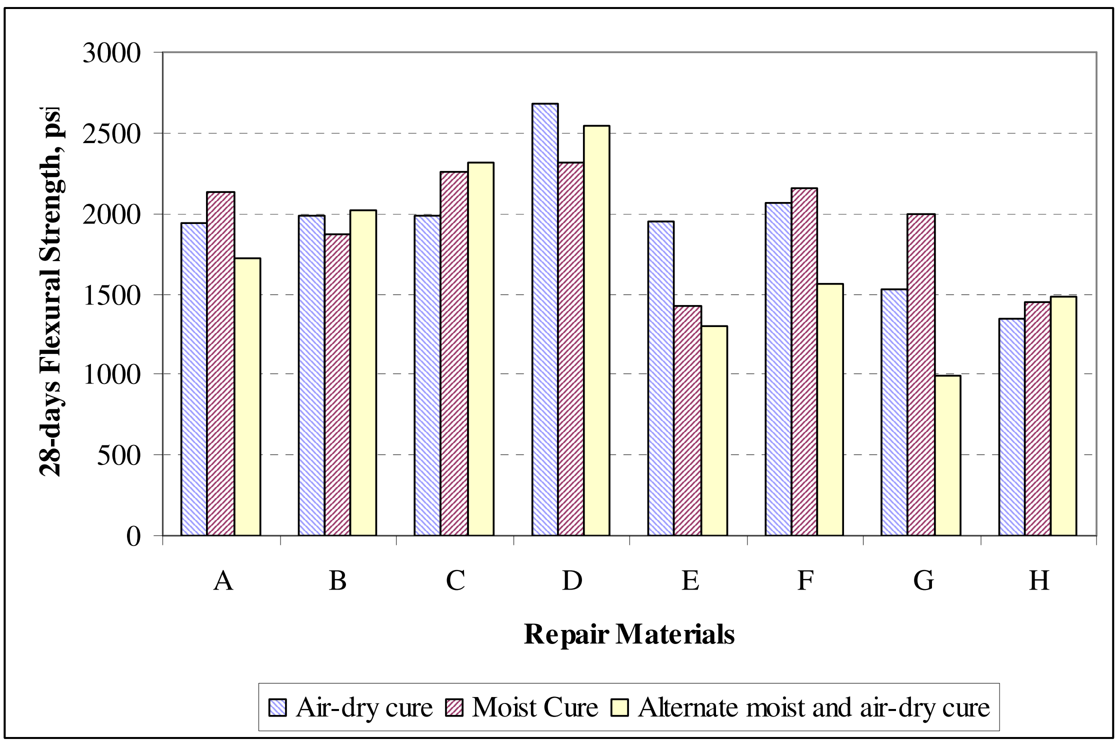


Figure 4.4 Flexural Strength at 28-days of the Repair Material in Different Curing Conditions

4.2. Durability Properties of the Repair materials

4.2.1. Drying Shrinkage

Figure 4.5 shows the drying shrinkage of the repair materials. These values are the average of four specimens as shown in the Appendix from Table A3 to Table A10. It can be observed that the repair materials D and G showed high drying shrinkage (i.e. > 0.1% at 28 days, Emmons et a.1993) Also, the repair materials A, B and C, which have moderate drying shrinkage value (i.e. > 0.05% at 28 days). These high values of drying shrinkage influence the compatibility, which is discussed in chapter six.

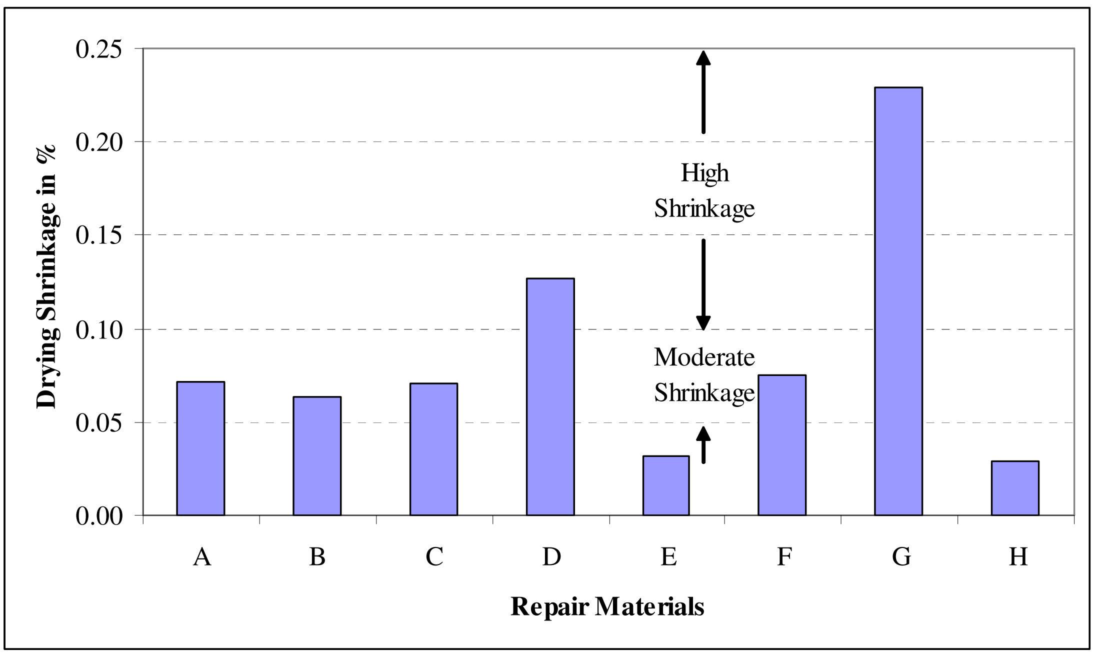


Figure 4.5 Results of Drying Shrinkage of the Repair Materials

4.2.2. Freeze-thaw resistance

Failure of repairs in highway and bridge decks is frequently caused by deterioration of substrate concrete and repair materials due to exposure to freeze-thaw cycling. Table 4.5 shows the durability factor and length change of the repair materials. These values are the average of two specimens as shown in the Appendix from Table A11 to Table A18. Higher is the durability factor better is the material to use in severe cold exposure condition. For instance, repair material C, D and F showed 100% durability factor. While, repair material E showed very poor durability factor (7%). It is obvious that poor durability factor repair materials can not be used in severe cold exposure condition.

Table 4.5 Freeze thaw results of the repair materials

Repair Materials	**Number of cycles**	**Durability Factor**	**Length Change (%)**
A	300	63	-0.36
B	300	95	0.01*
C	300	101	0.02*
D	300	103	0.01*
E	60	0	-0.22
F	300	99	-0.02
G	300	90	-0.07
H	300	95	-0.05

*Shrinkage of the specimen

4.2.3. Rapid Chloride Permeability

Figure 4.6 shows the chloride ion penetration of the repair materials as per ASTM C1202. These values are the average of two specimens as shown in the Appendix from Table A1 to Table A2. ASTM C1202 specifies- if 4000 coulomb charge passed through concrete in 6 hours, the concrete is considered to be highly permeable. It can be observed repair materials F and G are highly permeable. It is well established that very low permeability is desirable for a repair material. This method determines the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. However, this test method can produce misleading results when calcium nitrite has been admixed into a concrete (ASTM 1202). The repair materials are proprietary, material ingredients are unknown. Therefore, rapid chloride penetration may not be appropriate to measure the permeability of the repair materials. However, this gives a relative measure of permeability to chloride ions, which is the main ingredient for corrosion of reinforcements.

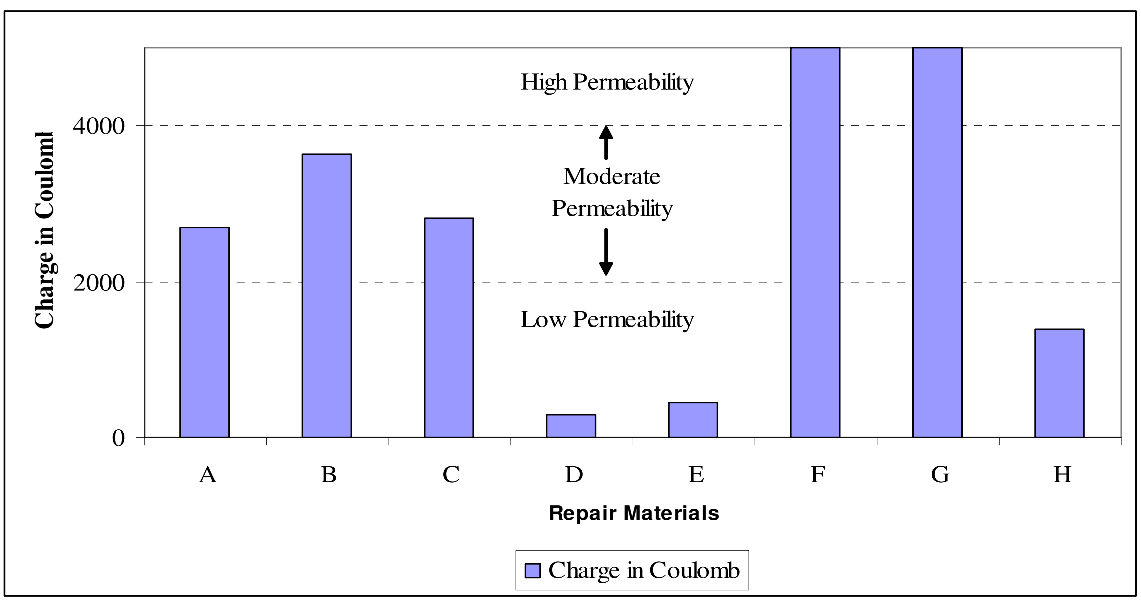


Figure 4.6 Results of Chloride Permeability Test of Repair Materials

CHAPTER FIVE
ANALYSIS OF SLANT SHEAR BOND STRENGTH OF REPAIR MATERIALS USING EXPERIMENTAL AND FINITE ELEMENT METHODS

5.1.Introduction

Typically, the cementitious repair materials are required to meet the specification ASTM C 928 – Standard Specification for Packaged, Dry, Rapid-Hardening Cementitious Materials for Concrete Repairs, or others developed based on individual experience of states (Austin et al.1999, Knab and Spring 1989, Austin and Robin 1993, and Abu-Tair et al.1996). Ideally, the selection of an appropriate repair material is a function of the type of structure, existing stress conditions at the location of the repair, environmental exposure conditions, and the time constraints placed on the repair operations. However, in practice the selection of repair material is most often based on achieving certain minimum compressive and bond strength in a short duration, so that the structure can be put into immediate service. The practical importance of the rapid setting and hardening behavior of repair materials is often reflected in the specifications imposed on the repair materials as seen in ASTM C928 specification.

While meeting the short term strength requirements ensures rapid opening of repaired structure to traffic, this practice does not ensure long-lasting, durable repairs. In particular, existing specifications do not consider the long-term properties of the repair materials, which can be significantly different from the properties measured at early ages. Also, the emphasis in existing specifications for selection of repair materials is placed on the properties of repair material alone with not much consideration given to the properties of the substrate concrete. In this regard, there can be a significant mismatch in properties such as modulus of elasticity, shrinkage potential, coefficient of thermal expansion and response to environmental exposure of the repair materials and that of the substrate concrete, leading to bond-related failures. The property of the composite section that is most affected by the incompatibility of the properties of repair and substrate concrete is the bond strength.

In the ASTM C 928 specification, the bond strength between the repair material and substrate concrete is determined using the slant shear test method as specified in ASTM C 882 test procedure. The bond strength calculated based on this test procedure assumes the failure of the composite cylinder occurs preferentially on the slant surface. However, previous research studies have shown that, the failure on the slant plane is not necessarily the case with all the repair materials (Austin et al.1999, Knab and Spring 1989, Austin et al.1995). The possible reasons for this deviation from the expected behavior include significant differences between the compressive strength, tensile strength, modulus of elasticity and poisson's ratio of the repair and the substrate materials. In this regard, the ASTM C 882 specification does not provide adequate guidance on the compatibility of the substrate mortar specimens and the repair materials.

Differences in surface preparation are also likely to result in significant differences in the failure mode observed in the slant shear test method (Austin et al.1999, Knab and Spring 1989, Austin and Robin 1993, and Abu-Tair et al.1996). ASTM C 882 specifies the use of sand blasting and dry brushing for preparing the slant surface of the substrate mortar specimens prior to bonding with the repair material. However, there is no guidance on the type of sand to be used, or any specific degree of roughness to be achieved on the prepared surface.

Another factor that is likely to influence the bond strength is the type of curing that the composite cylinders receive. Although, ASTM C 882 specifies curing as per ASTM C 192, the curing of the repaired sections in field conditions is likely to be less than ideal in nature, and therefore may influence the bond.

This chapter investigates the influence of selected variables on the bond strength of the composite cylinder as measured using the ASTM C 882 slant shear test procedure. These include:

(1) The effect of differences in compressive strength and split tensile strength between the substrate mortar and the repair material.

(2) The effect of difference in surface textures of the slant surface generated using different blasting media.

(3) The effect of different curing conditions.

Also, a simple finite element model of the composite section was studied to investigate the influence of variations in the properties of the repair and substrate material on the stress distribution across the composite specimen. The specific properties varied in this investigation were modulus of elasticity. The findings from the finite element model are compared with experimental results.

5.2. Research Significance

A wide variety of rapid set patching materials are used for repair of concrete structures, bridges and pavements. Often the approval of these materials by a state highway agency depends on achieving a specified bond strength along with other parameters such as compressive strength and setting time. Slant shear test method as per ASTM C 882 standard is widely used in the United States to indicate the bond strength of repair materials. However, performance of repair materials has shown that this test method does not adequately characterize the true bond strength of the repair materials due to some inherent shortcomings. In this research, selected factors influencing the measurement of the bond strength in the slant shear test procedure have been investigated. In particular, the influence of the difference in the compressive strength and split tensile strength of the repair materials and the substrate concrete on the bond strength of the composite specimen has been investigated. In addition, the influence of quality of the prepared surface and the curing conditions on the bond strength has been studied. The potential reasons behind the abnormal failure of the composite cylinders were explored using both experimental and finite element based methods. Based on the findings from this research, suggestions to improve the test method are presented.

5.3. Experimental Test Methods

Following test methods were used to investigate the bond strength between repair material and substrate mortar. Details of these test methods are explained in chapter three.

(a) Slant Shear bond Strength

(b) Compressive Strength

(c) Split Tensile Strength

5.4. Experimental Methodology

In this investigation, the influence of selected factors on the bond strength of eight different repair materials as determined using ASTM C 882 test method was investigated. The specific factors include relative difference in specific properties of the repair material and the substrate concrete, quality of the prepared substrate surface on which the repair material is bonded, and the curing condition of the composite specimen after the bonding of the repair material. The specific properties of the repair materials and the substrate mortar considered include compressive strength and split tensile strength. In addition, the influence of differences in the modulus of elasticity of the repair material and substrate material on the stress distribution in a composite specimen was investigated using a finite element model.

The experimental program consisted of casting 96 substrate mortar specimens in 3-in. diameter x 6-in. tall plastic cylinder molds that were fitted with a specially designed inset to create a slant surface for bonding the repair materials. The dimensions of the test specimen are shown in the Figure 2.7. Sixteen batches of mortar were prepared to cast six slant substrate specimens per batch. In addition, six 2-in. cubes and six 3-in. x 6-in. cylinders were also prepared to determine the compressive and tensile strength of the mortar, respectively, at 1 day and 28 days. Each of these tests were conducted on three test specimens cured in dry-air and moist curing conditions. The mixture proportions and the mixing procedure were identical in preparing substrate specimens in each of the sixteen batches. However, when composite cylinders with repair materials were prepared at later ages, six substrate specimens from the same batch were used in bonding a given repair material to avoid any variability. The proportions of the materials used in preparing the substrate mortar were based on a cement-to-sand mass ratio of 1:2.5. A water-to-cement ratio of 0.45 was used in all batches to achieve a uniform compressive and split tensile strength among the substrate specimens of all batches.

Following effects were observed to investigate the bond strength between repair material and substrate mortar.

(a) Effect of Differences in Strength of Substrate and Repair Material on Bond Strength

(b) Effect of Differences in Surface Textures on Bond Strength

(c) Effect of Differences in Curing Methods on Bond Strength

5.4.1. Effect of Differences in Strength

In order to investigate the influence of differences in compressive strength and split tensile strength of the repair and substrate materials on the bond strength of the repair material, composite cylinder specimens were prepared as per the ASTM C 882 test method. The composite cylinders with a given repair material were prepared on the day when the substrate cylinders were 35 days old (28 days moist cured and 7 days air-cured). The composite cylinders were de-molded 24 hours after casting, and tested in two different curing conditions – air-dry curing and moist curing. The composite cylinders were tested for bond strength as per ASTM C 882 procedure after 1 day and 28 days of casting. Along with the slant shear test on composite cylinders, cubes and cylinders prepared from the same batch of mortar were tested to determine the compressive and tensile strength of the mortar, respectively. In these tests the repair materials showed very rapid changes in their properties up to 28 days. The substrate mortar specimens, cast 35 days earlier than repair materials, did not exhibit significant changes in their compressive and split tensile strengths when tested alongside the repair materials. The details of these tests are provided in the results section.

As a result of the disparity in the rate of strength gain between the repair materials and substrate mortar, the bond strength of a given repair material determined at any particular age reflected the influence of a unique combination of properties of the repair and the substrate materials. Depending on the age of testing of the composite cylinder for bond strength, the compressive strength and split tensile strength of the repair materials were lower, similar or greater than the strength of the substrate mortar. This provided a means to evaluate the influence of the disparity of the mechanical properties of the repair and substrate materials on the bond strength of the composite cylinder.

5.4.2. Effect of Differences in Surface Textures

ASTM C 882 test method specifies that the surface of the substrate cylinder should be sand-blasted and dry-brushed before applying the repair material. However, no specific guidance is provided on the quality of the sand to be used in the blasting. In order to study the influence of roughness of the sand-blasted surface of the substrate mortar specimen on the bond strength of the composite cylinder, coarser grit quartz sand (with fineness modulus of 1.73) and finer grit quartz sand (with a fineness modulus 1.41) were used. The authors understand that the fineness modulus of the sand is not sufficient to characterize the surface texture. However, the objective of this test was to study the qualitative influence of two different surface textures in addition to the variables of the strength and the curing types on the bond strength. The process of sand blasting itself was identical with both the blasting media use in this study. The two blasting media resulted in different surface texture that was visually distinguishable. However, no quantitative measurement of the surface roughness was conducted in this research study. With each of the 8 repair materials, composite cylinders were cast using substrate specimens prepared with each of the two blasting media. The bond strength was measured at 28 days to assess the effect of the differences in surface texture of the prepared substrate specimen.

5.4.3. Effect of Differences in Curing Methods

To investigate the effect of curing methods on the bond strength of the composite cylinders, two different types of curing conditions were employed. After casting the composite cylinders using the mature substrate mortar specimens, the composite cylinders were cured in two different curing conditions, and tested at 28 days of age. The two curing conditions employed in this study are:

(i) Dry-air cure (23ºC and 50% Relative Humidity)

(ii) Moist cure (23ºC and 100% Relative Humidity)

From each batch of the repair materials, 2-in cubes and 3-in x 6-in cylinders were prepared to measure corresponding compressive and split tensile strength of the materials, to monitor the influence of curing method on these properties.

5.4.4. Finite Element Model

In order to assess the influence of differences in modulus of elasticity of the repair materials and substrate mortar on the bond strength of the composite specimen, a simple finite element model (FEM) developed in SAP2000 program was used. A composite prismatic section of 3-in x 3-in x 6-in. dimensions as shown in Figure 5.1, consisting of repair material over the substrate mortar was chosen for this analysis. As the primary objective of the FEM investigation was only to study the relative distribution of the stresses between the repair material and the substrate material, a prismatic section was chosen in place of the cylindrical section because of the convenience in constructing the FEM model and in interpreting the results.

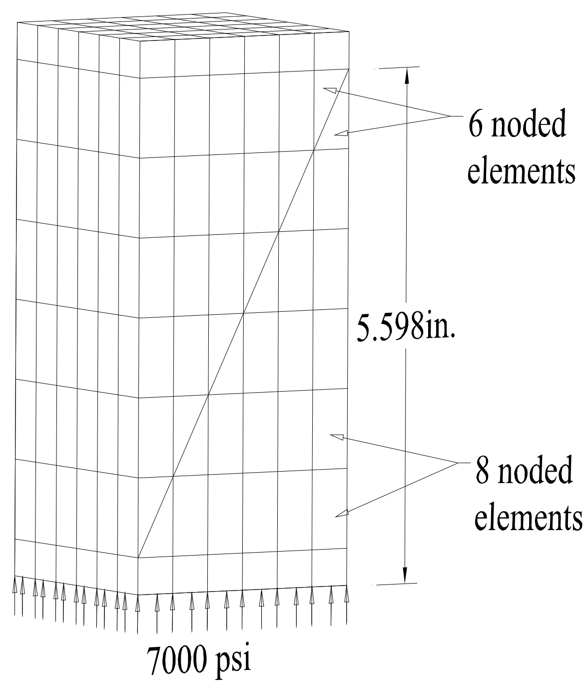


Figure 5.1 Finite Element Model and Loading

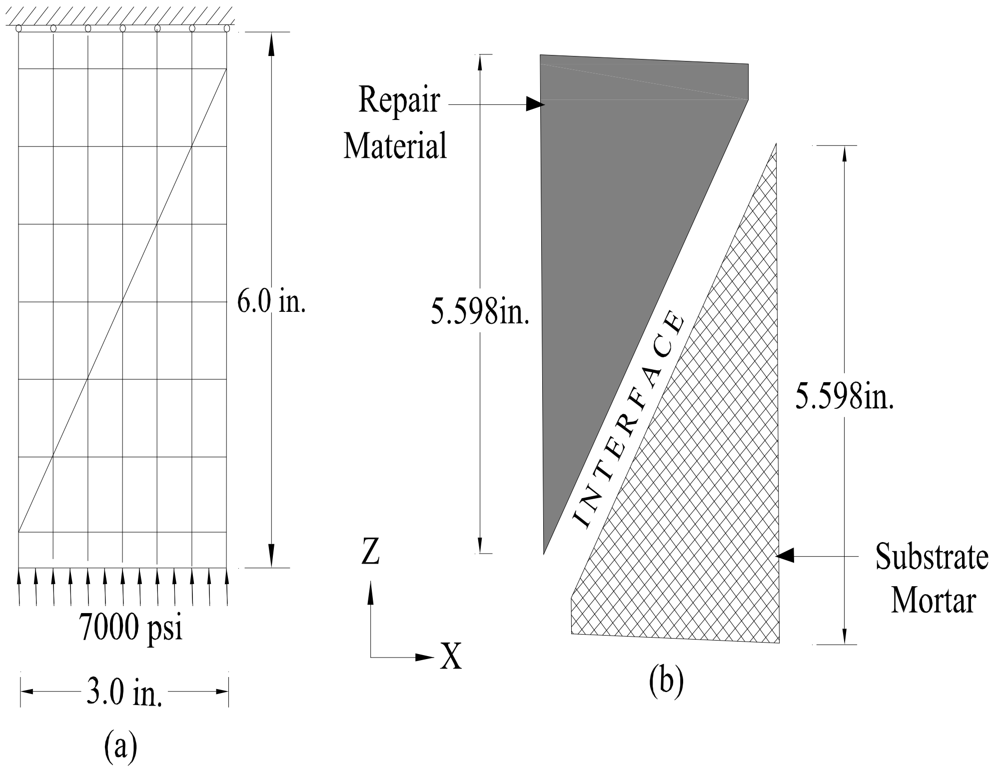
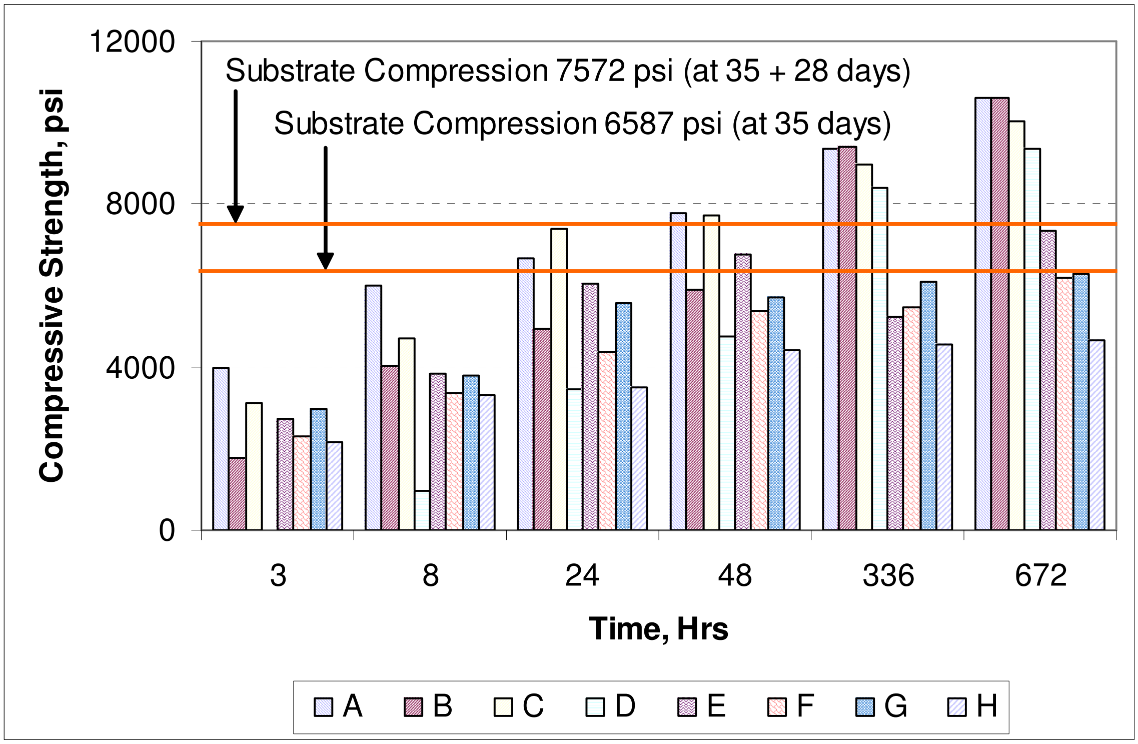


Figure 5.2 Cross Section of the Model and Possible Failure Locations

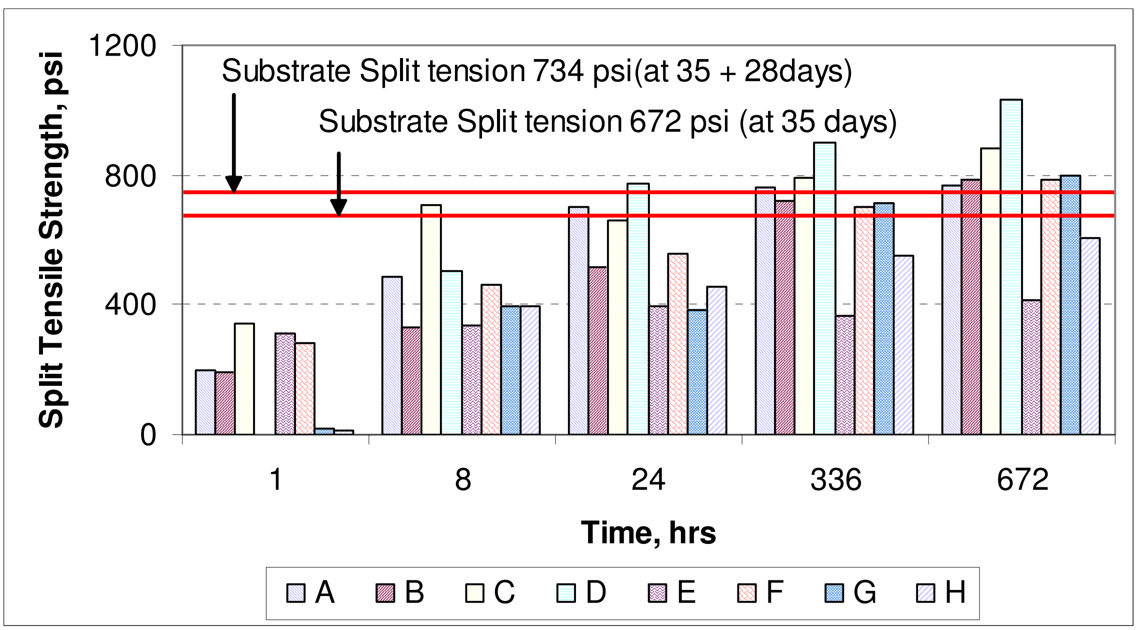
The composite section is modeled with six and eight noded solid elements (linear) as shown in the Figure 5.1. Six noded elements were used near the interface, and the remaining portion of the section was modeled with the eight noded elements. The top nodes of the composite sections were restrained against vertical movement (u3=0). On the bottom elements a uniform surface pressure of 7000 psi was applied as shown in Figure 5.2, analogous to the compression testing machine. The stiffness of the elements above the slant surface was assigned the same value as the repair material. The stiffness of the elements below the slant surface was assigned that of the substrate material. Modulus of elasticity of the substrate material is assumed 4.5 x 10^6 psi, and the modulus of elasticity of repair materials was varied to achieve a modular ratio (i.e. ratio of modulus of repair material-to-modulus of substrate material) ranging from 1.3 to 0.7, keeping the poisson's ratio of both materials at 0.2. The model was analyzed to assess the stress concentrations in the composite section as a function of the rapidly changing properties of repair materials relative to substrate mortar.

5.5. Results and Analysis

In the present investigation the compressive strength and the split tensile strength of the substrate mortar at 35 days was found to be 6,587 and 672 psi, respectively. It was observed that in the subsequent 28 days during which the composite cylinders were cured, the substrate mortar registered only an additional 985 psi increase in compressive strength and 62 psi in split tensile strength. In contrast, test specimens of repair materials cast alongside the composite cylinders exhibited a rapid gain in compressive strength and split tensile strength within 28 days, ranging from 4,500 to 12,000 psi. Figure 5.3.a and b show the development in compressive strength and split tensile strength of the eight repair materials considered in this study. The compressive strength and the split tensile strength of the substrate mortar at 35 days and 35 + 28 days of age are shown in Figures 5.3.a and b for reference, respectively.



a) Compressive strength development of repair materials with age

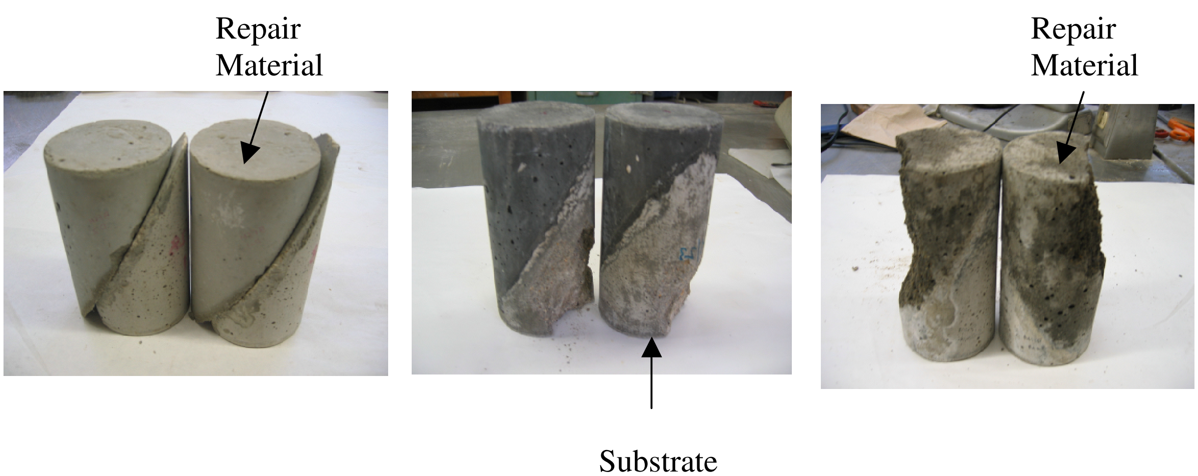


b) Split Tensile Strength Development of Repair Materials with age

Figure 5.3 Compressive and Split Tensile Strength Developments of Repair Materials Relative to Substrate Mortar

It is apparent from observing the data in Figures 5.3.a and b that depending on the specific repair material, significant difference exists between the properties of the repair material and the substrate at any given age. This disparity in strengths can be expected to influence the failure mode and the bond strength determined in the composite cylinder. Similarly, the texture of the bonding surface and the curing conditions can be expected to have an influence on the properties of composite cylinders.

In conducting the bond tests on the repair materials, three different modes of failures were observed as shown in Figure 5.4. Figure 5.4a shows the failure on the slant surface indicating a failure of the bond between the repair and substrate material. Figures 5.4b and c show the failure of the composite cylinder in substrate and repair material, respectively, indicating a weaker material strength than the bond strength at the interface.



(a) Interface Failure (b) Substrate Failure (c) Repair Material Failure

Figure 5.4 Failures of the Composite Slant Sections

In this study, a compressive strength ratio and split tensile strength ratio (i.e. strength of repair material/strength of substrate mortar) is defined to characterize the influence of disparity in strength on the failure mode of the composite cylinder. In addition, a composite compressive strength was determined to assess the load carrying capacity of specimens in which the failure did not occur on the slant surface. Results and analysis of these investigations are presented.

5.5.1. Effect of Differences in Strength

Table 5.1 shows the compressive strength ratio and the bond strength of the air-cured specimens, in which the substrate surface is blasted with finer grit sand. The compressive strength of the repair material was determined at 1 day and 28 days after casting the repair material specimens, while the corresponding compressive strengths of the substrate mortar were obtained at 36 days and 63 days after casting the test specimens. In these tests, the repair materials were air-cured, while the substrate material was cured for 28 days in moist curing followed by subsequent curing in air-dry conditions. Table 5.1 also shows the bond strength of the repair material at 1 day and 28 days, after casting the repair material over the substrate mortar. It can be observed from Table 5.1 that the bond strength increased rapidly with age for all the repair materials. Also, the bond strength increased with the increase in the compressive strength ratio (see Figure 5.5). In these tests, the failure of the composite cylinders occurred on the slant surface for all repair materials, in other words a pure bond failure.

Table 5.1 Bond Strength of Fine Grit Sand Blasted Sections under Air-Dry Curing

Repair material	Compressive Strength Ratio		Actual Bond Strength (psi)		Failure Mode
	1-day	28-days	1-day	28-days	
A	1.02	1.47	1695	2669	Interface
B	0.80	1.46	2186	2623	Interface
C	1.12	1.23	2041	1935	Interface
D	0.49	1.08	643	1941	Interface
E	0.92	1.03	2113	3033	Interface
F	0.66	0.89	1937	2131	Interface
G	0.85	0.81	556	1031	Interface
H	0.53	0.65	1699	1749	Interface

Tables 5.2 and Table 5.3 show the 28-days results of the compressive strength ratio, tensile strength ratio, and the bond strength of composite cylinder for air-cured and moist-cured specimens, respectively. In these tests, the slant surface of the substrate mortar was sand blasted with coarser grit sand. In cases where the failure of the composite cylinder was not on the slant surface, a composite compressive strength was determined. Also, Tables 5.1, Table 5.2, and Table 5.3 indicate the failure type observed in the composite cylinders.

It can be observed from the results in Tables 5.2 that in all repair materials (A, B, C, F, G, and H) failure in the composite cylinder occur in the interface. It was also observed that the failure of the composite cylinders occurs on the interface, if the compressive strength ratio between repair materials and substrate materials is less than

1.50. This threshold appears to be valid, irrespective of curing conditions of the composite cylinders. The repair materials D and E had a compressive strength ratio of 1.24 and 0.93 in air-cure conditions. However, they failed in the substrate and the repair material, respectively. The unique behavior of the repair materials D and E appears to be due to their deviation in split tensile strength ratio compared to other comparable repair materials. In case of repair material D, the split tensile strength ratio is the highest (1.22 in air-cure and 1.54 in moist cure) compared to values of other repair materials studied in this research (see Tables 5.2 and Table 5.3). In case of repair material E, the split tensile strength ratio was lowest among the eight repair materials (0.54 in air-cure and 0.62 in moist cure) compared to values of other repair materials studied in this research (see Tables 5.2 and Table 5.3).

When the compressive strength ratio is approximately 1.0 or less, the repair material is either similar or inferior in compressive strength compared to substrate mortar. In these situations, it is evident from observing the data in Tables 5.2 and Table 5.3 that the failure occurs either in the repair material or on the slant surface. The specific failure mode depends on tensile strength of the repair material.

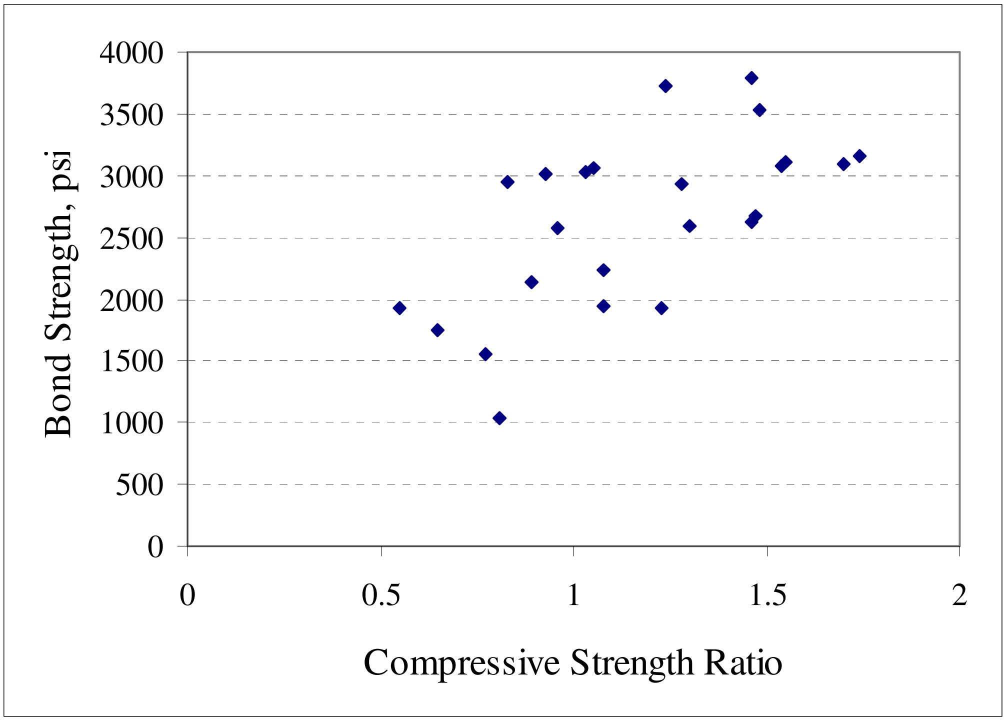


Figure 5.5 Compressive Strength Ratio versus Bond Strength

Table 5.2 28 Days Strength Results of Coarser Sand Blasted Specimen in Air-Dry Curing

Repair Material	Substrate* comp. Strength (psi)	Repair Material comp. Strength (psi)	Comp. strength Ratio	Split tensile Strength Ratio	Minimum Bond Strength (ASTM C 882)	Actual Bond Strength (psi)	Failure Mode
A	7289	10,615	1.46	1.09	3785	3785	Interface
B	7166	10,624	1.48	1.04	3527	3527	Interface
C	7713	10,048	1.30	1.15	2598	2598	Interface
D	7554	9339	1.24	1.22	3720	-	Substrate
E	7937	7347	0.93	0.54	3005	-	repair material
F	8107	6214	0.77	1.05	1562	1562	Interface
G	7314	6080	0.83	0.74	2950	2950	Interface and repair material
H	8088	4436	0.55	1.03	1926	1926	Interface and repair material

* The Substrate compressive strength represents the average strength of the specimen from same batch of mortar used for a particular repair material.

Table 5.3 28 Days Strength Results of Coarser Sand Blasted Specimen in Moist-cure

Repair Material	Substrate* comp. Strength (psi)	Repair Material comp. Strength (psi)	Comp. strength Ratio	Split tensile Strength Ratio	Minimum Bond Strength (ASTM C 882)	Actual Bond Strength (psi)	Failure Mode
A	6740	11,703	1.74	1.14	3164	-	Substrate
B	6110	10,398	1.70	1.17	3093	-	Substrate
C	6299	9677	1.54	1.31	3078	-	Substrate
D	6163	9556	1.55	1.54	3104	-	Substrate
E	6267	6797	1.08	0.62	2232	-	repair material
F	6509	8354	1.28	1.17	2932	2932	Interface and substrate
G	5993	6298	1.05	1.06	3053	3053	Interface and substrate
H	6357	6130	0.96	0.9	2580	2580	Interface and repair material

* The Substrate compressive strength represents the average strength of the specimen from same batch of mortar used for a particular repair material.

It is well known that concrete and mortars are weak in tension. Therefore, when a compressive load is applied on a concrete or mortar cylinder the failure occurs due to the principal tensile stresses generated in an orthogonal direction to the applied stress. In a composite cylinder in which the repair material is bonded to substrate mortar on a slant surface, the applied compressive load exerts a complex state of stress on the slant surface which is dominated by shear stresses. However, a principal tensile stress is also exerted in a direction perpendicular to the applied compressive load. If the bond between the repair material and the substrate material is good to sustain the shear stresses generated on the slant surface, then the failure mode in the composite cylinder is dictated by the tensile strength of the repair material. Therefore, it is observed that in repair materials such as E and H, which are inferior in tensile strength than substrate mortar, failure occurred in the repair material rather than at the interface.

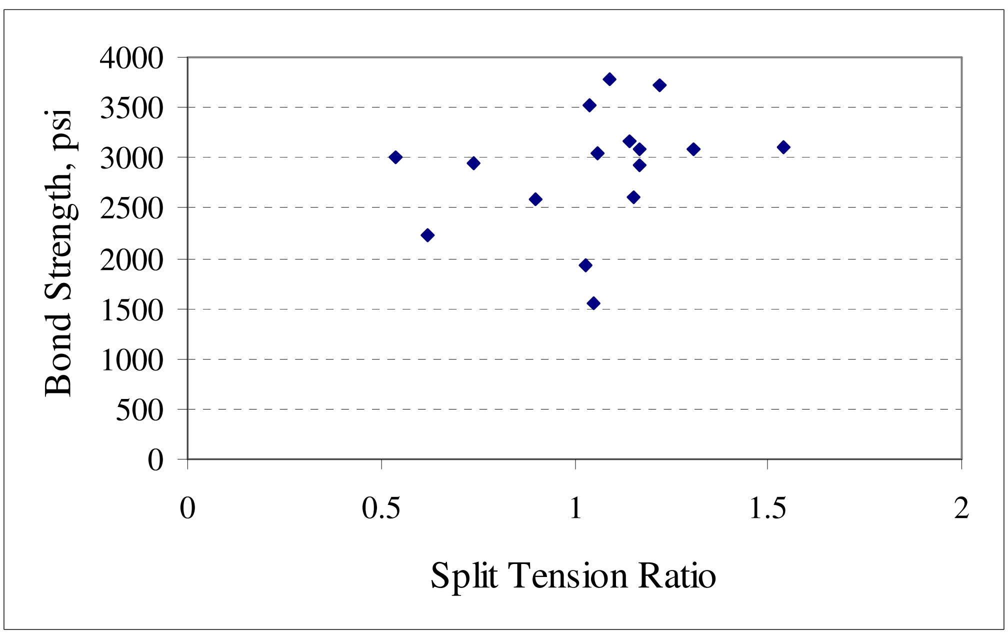


Figure 5.6 Split Tensile Strength Ratio versus Bond Strength

It is therefore necessary to proportion a substrate mortar in such a way that its compressive strength as well as tensile strength should have values close to the corresponding strengths of the repair material at the time of testing, so that the failure would occur on the slant surface instead of substrate or in the repair materials. This will yield a true bond strength of the repair material.

5.5.2. Effect of Differences in Surface Texture

When a compressive load is applied on a composite cylinder in which a repair material is bonded to a substrate material on a slant surface, it is understood that the failure takes place on the weakest plane. In this regard, the texture of the bonding surface is an important parameter that governs the magnitude of the bond strength. Figure 5.7 shows the 28-day bond strength data of repair materials in which the slant surface of the substrate specimen was prepared using fine grit sand and coarse grit sand, respectively. It can be observed from the data that the bond strength was significantly higher in test specimens in which, the substrate surface was textured with coarse grit sand blast compared to those that were textured with fine grit sand, with exception of repair material F. It should also be noted that the mode of failure in the composite cylinder is also governed by the surface texture. For instance, composite cylinders prepared with repair materials D and E failed at the interface when textured with fine grit sand blast (see Figure 5.7). However, the composite cylinders prepared with same repair materials and cured similarly, did not fail on the interface when textured with the coarse grit sand blast because of the improved bond strength. These results validate the findings of previous studies on surface-finish influences on the slant shear strength (Austin et al.1999, Knab and Spring 1989, Austin and Robin 1993, and Abu-Tair et al.1996). Therefore, the author believe that the ASTM C882 specification should include a requirement to achieve a degree of roughness on the substrate mortar surface, before casting repair material over it. In the present research, the surface texture was evaluated only in qualitative terms. Further work is needed in this regard to quantify the surface texture on the substrate mortar.

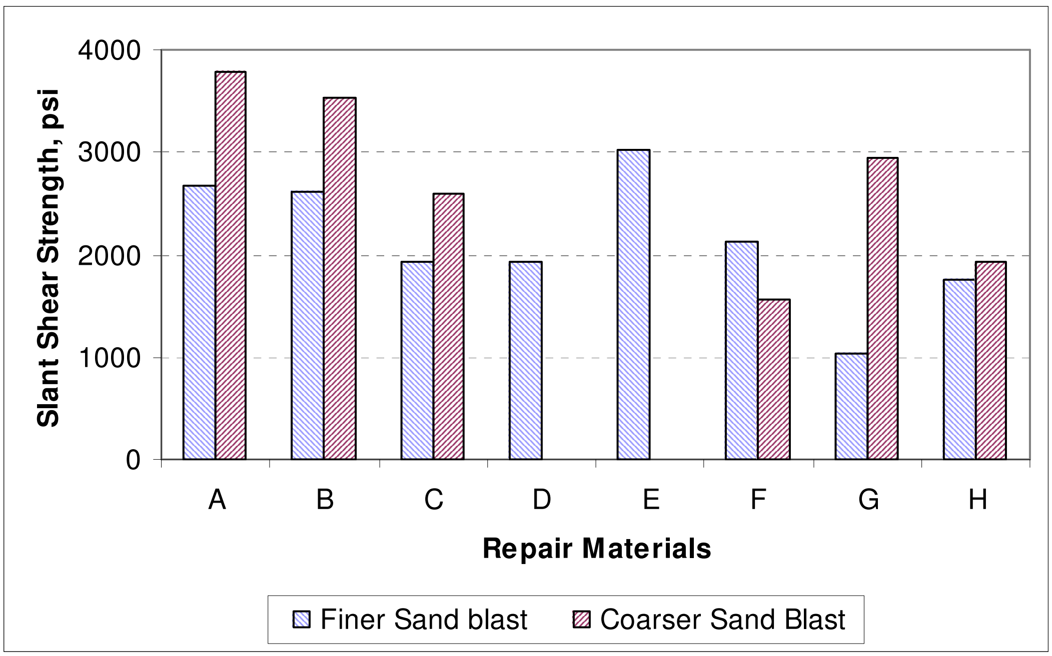


Figure 5.7 28 days Bond Strength of the Composite Section in Two Different Surface Textures

5.5.3. Effect of Differences in Curing Methods

Tables 5.2 and Table 5.3 show the compressive strength, split tensile strength, and the bond strength of the substrate and the repair materials in air-cured and moist-cured conditions, respectively. It can be observed from the data that the compressive strength ratio and split tensile strength ratio of repair and substrate materials under moist-cure conditions were higher than those observed in air-cure conditions. The improved compressive strength ratio and the split tensile strength ratio in moist cure conditions are also reflected in the nature of the failure observed in the composite cylinders. For instance, the three repair materials (A, B, C) which exhibited a compressive strength ratio ranging between 1.46 and 1.30 in air-cured condition failed at the interface. The same three repair materials exhibited a compressive strength ratio ranging between 1.74 and 1.54 in moist-cured condition, failed in the substrate. This illustrates the improved bond strength in these materials with moist-cure conditions relative to air-cure conditions.

5.5.4. Finite Element Analysis

Figure 5.8 shows the distribution of principal compressive stress in the composite section as a function of the modular ratio. It can be observed from Figure 5.8b that at a modular ratio of 1.0, the stress distribution in the composite section is uniform. However, as the modular ratio deviates from 1.0, stress concentrations are more either in the substrate or in repair material in addition to the interface depending upon the modular ratio. For instance, when the modular ratio is 1.3, the higher compressive stress concentration occurs on the substrate face as shown in Figure 5.8a. This indicates that when the repair material is significantly stronger than the substrate mortar the failure preferentially occurs in the substrate mortar as seen in Figure 5.4b. Incidentally, it was observed in experimental findings that when the repair material is stronger, the associated bond strength is higher. This situation forces the failure to occur preferentially in the substrate material instead of interface. However, when the modular ratio is 0.70, (i.e. the repair material is weaker than the substrate material), the higher compressive stress concentration occurs on the repair material face and the interface. In this case, depending on the bond strength of the composite section, the failure occurs either on the repair material face or at the interface as seen in Figure 5.4c. The findings from the finite element analysis on the influence of modular ratio on bond strength and failure mode validates the experimental findings reported in the previous section.

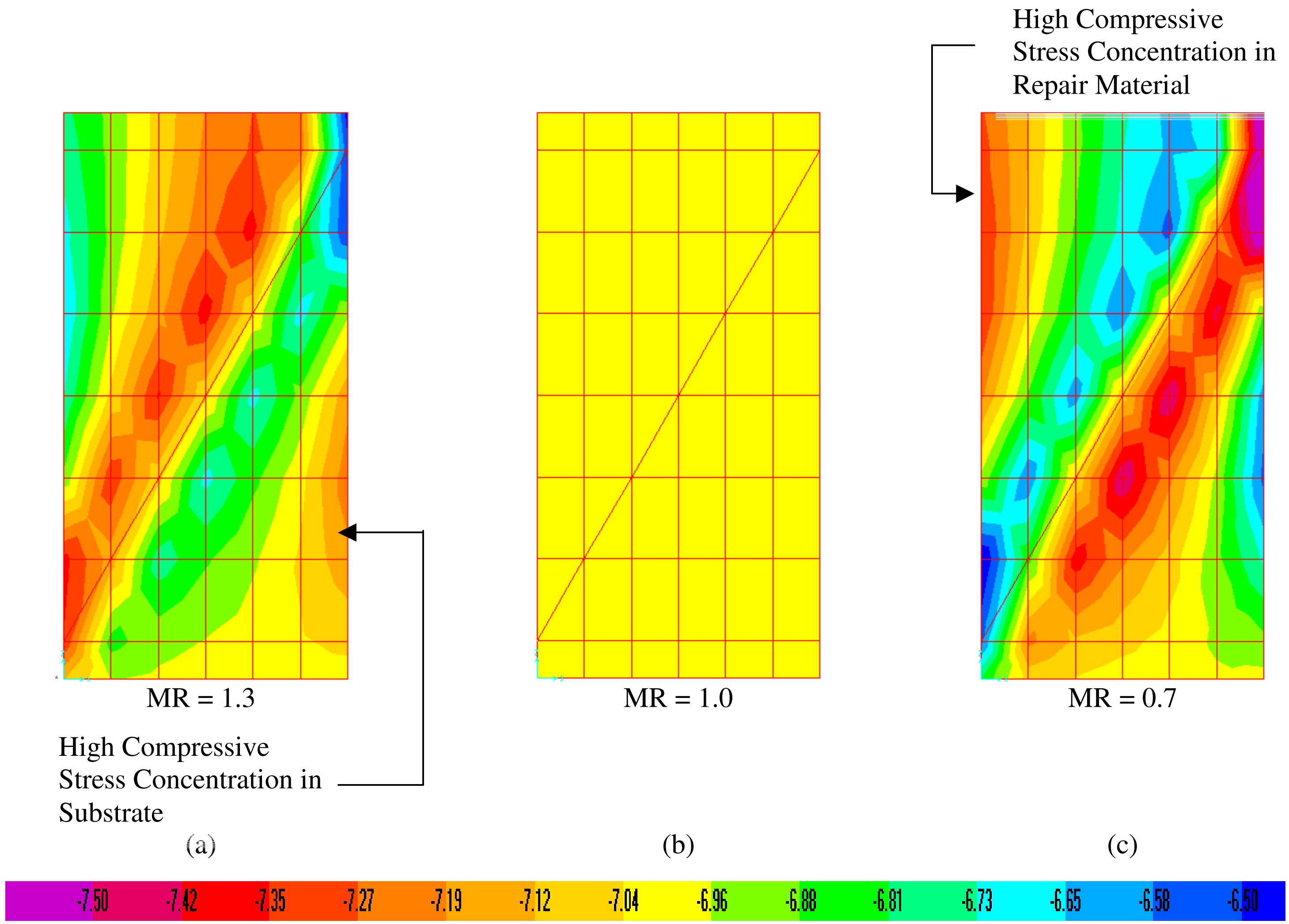


Figure 5.8 Principal Compressive Stress (in ksi) distributions in the composite section

5.6. Conclusions

Based on the results from the experimental program and the finite element analysis it can be concluded that bond strength in the slant shear test method is dependent on the compressive and tensile strength ratios of the materials used and the surface texture of the substrate mortar. Coarser surface texture yielded higher bond strengths in all the repair materials. When adequate surface texture on the substrate mortar section was provided, the failure in the composite cylinder is governed by a combination of compressive strength ratio and tensile strength ratio parameters. In case of composite cylinders that failed in substrate the compressive strength ratio generally exceeded 1.50 and the tensile strength ratio was close to 1.0. However, the results from this investigation are limited to eight repair materials and additional data is needed to define more precisely the limits of compressive and tensile strength ratio within which a particular failure mode occurs. Findings from finite element model indicated the importance of modular ratio on the mode of failure in the composite cylinders and validated the experimental findings. Finally, the type of curing also influences the observed bond strength. For a given repair material, moist cured test specimens showed significantly improved actual bond strength compared to air-cured specimens.

CHAPTER SIX
ANALYSIS OF COMPATIBILITY BETWEEN REPAIR MATERIAL AND SUBSTRATE CONCRETE USING SIMPLE BEAM WITH THIRD POINT LOADING

6.1. Introduction

Selection of these materials should be such that the repair material is compatible with the substrate concrete. Material properties such as compressive strength, tensile strength, stiffness, poisson's ratio etc., are important to study before selecting a repair material. Drying shrinkage of hardened repair material is also an important property to establish the compatibility with the substrate concrete. By the time repair materials are cast over the substrate concrete, the substrate concrete would have already gone through numerous cycles of drying and wetting, and consequently would exhibit only minimal reversible shrinkage. Drying shrinkage of the repair material induces tensile stresses at the interface between repair and substrate materials, potentially causing failure. Drying shrinkage values of repair materials in excess of 0.05%, and 0.1% at 30 days are considered to represent moderate and high levels of drying shrinkage, respectively, that can potentially result in premature failures (Emmons et al.1993).

It is generally observed that a repair section in concrete structures is mostly performed at the joints or in the tension area (Poston et al. 2001). Tension is induced in the concrete by bending of the structure due to loading or due to environment conditions. Therefore, flexure test method would be an appropriate method to study the compatibility between repair and substrate material. Czarneck et al. 1999 developed an experimental method using simple beam with third- point loading. The failure modes (compatible or incompatible) were categorized as shown in the Figure 6.1

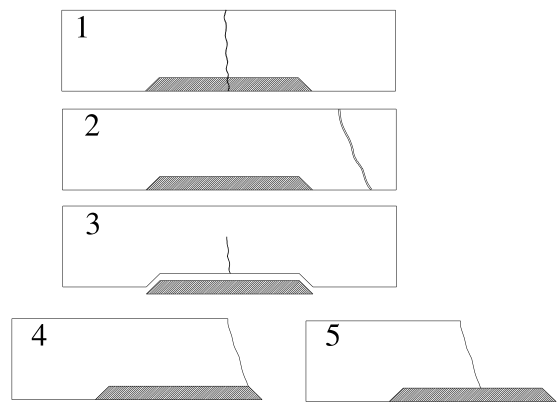


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Figure 6.1 Probable failures of the Composite beam; 1,2 – Compatible; 3, 4 and 5- Incompatible

In this chapter, the author investigates the compatibility between repair material and substrate concrete using a test method similar to that developed by Czarneck et al. In addition, load-deflection behaviors of the composite section (i.e. substrate concrete with repair material) were evaluated. A composite section factor was developed to evaluate the compatibility between the materials. The composite section factor is defined as the ratio of flexural strength of composite section to that of the control substrate section. Also in this study, the effect of three different curing methods on the failure characteristics of composite section was investigated.

A simple finite element model of the composite section was studied to investigate the influence of variations in the properties of the repair and substrate materials on the stress distribution across the composite specimen. Load-deflection curves of the composite section with different properties of repair material were developed to compare with the experimental findings. The specific properties varied in this investigation were modulus of elasticity.

6.2. Research Significance

A wide variety of rapid set patching materials are used for repair of concrete structures, bridges and pavements. To achieve durable repairs, it is necessary to consider the factors affecting the selection of repair materials as parts of a composite system. Among many factors, compatibility between repair material and existing concrete is an important factor in the selection process. Information on the material properties that are affecting compatibility between repair and substrate concrete is limited, and most often the studies are conducted on individual repair materials rather than on the composite sections, to assess the compatibility. This research study investigates the potential factors influencing the compatibility between repair and substrate on a composite section beam using both experimental and finite element based methods. The findings of this research can help the highway agencies or the owners of the concrete structure in selecting repair materials for partial depth concrete repairs.

6.3. Experimental Test Methods

Following test methods were used to investigate the bond strength between repair material and substrate mortar. Details of these test methods are explained in chapter 3.

(a) Third point loading beam Test of composite beam

(b) Compressive Strength

(c) Flexural Strength

(d) Split Tensile Strength

(e) Drying Shrinkage

6.4. Experimental Methodology

In this study, the compatibility of eight different repair materials with substrate concrete was investigated by determining flexural strength of composite beam, the load-deflection behavior, and the failure mode of prism tested as per standard and modified ASTM C 78 test method. The specific factors include relative difference in specific properties of the repair material and the substrate concrete, and the curing condition of the composite specimen after the bonding of the repair material. The specific properties of the repair materials and the substrate concrete considered include compressive strength, flexural strength and drying shrinkage. In addition, the influence of differences in the modulus of elasticity of the repair material and substrate material on the stress distribution in a composite specimen was investigated using a finite element model.

Following effects were observed to investigate the compatibility between repair material and substrate concrete.

(a) Effect of Differences in Strength

(b) Effect of Differences in Curing Methods

6.4.1. Effect of Differences in Strengths

In order to investigate the influence of differences in compressive strength and flexural strength of the repair and substrate materials on compatibility between the materials, composite section specimens were prepared. The composite sections with a given repair material were prepared on the day when the substrate concrete was 35 days old (28 days moist cured and 7 days air-cured). The composite sections were de-molded 24 hours after casting repair materials, and stored in three different curing conditions – air-dry curing, moist curing, and alternate moist and air-dry curing. Along with the composite sections, cubes and the prismatic sections prepared from the same batch of substrate and repair materials used for evaluating the load deflection behaviors, compressive strength, and flexural strength. These specimens were also stored in same curing regime before testing. In these tests the repair materials showed very rapid changes in their properties up to 28 days, while the substrate concrete specimens, 35 days earlier than repair materials, did not exhibit significant changes in their compressive and flexural strengths when tested alongside the composite sections. The details of these tests are provided in the results section.

As a result of the disparity in the rate of strength gain between the repair materials and substrate concrete, the flexural strength and the deflection at center of the composite section for a given repair material determined at any particular age reflected the influence of a unique combination of properties of the repair and the substrate materials. Depending on the age of testing of the composite section for compatibility, the compressive strength and flexural strength of the repair materials were either lower or higher than the strength of the substrate concrete. This provided a means to evaluate the influence of the disparity of the mechanical properties of different repair materials and substrate concrete on the compatibility of the composite section.

6.4.2. Effect of Differences in Curing Methods

The purpose of this study is to investigate the effect of curing methods on compatibility of the composite sections. Three different types of curing conditions were employed, considering the probable conditions on the field. The three curing conditions are:

(iii) Air- dry cure (23ºC and 50% Relative Humidity)

(iv) Moist cure (23ºC and 100% Relative Humidity)

(v) Alternatively- 3 days Moist cure (23ºC and 100% Relative Humidity) and 3 days air cure (38ºC and 50% Relative Humidity)

After casting the composite sections using the mature substrate prismatic specimens, and subjecting the composite beam to each of the three curing regimes, the composite sections were tested for load-deflection behavior, flexural strength and failure modes at 28 days of age. The results obtained from these curing methods were compared with the drying shrinkage values of the repair materials.

6.4.3. Finite Element model

In order to assess the influence of differences in Modulus of Elasticity (MOE) of the repair materials and substrate concrete on the compatibility of the composite specimen, a simple finite element model (FEM) was developed in SAP2000 program, as shown in Figure 6.2. The model consists of substrate material, repair material, and 0.1 in thick interface area between repair and the substrate materials. The objectives of the FEM investigation were to study:

(a) The relative distribution of the stresses between the repair material and the substrate material with different MOE of the materials.

(b) The compatibility between repair and substrate using deflection at the center of the composite section, when loaded in third-point flexure.

The composite section was modeled with three and four-noded shell-thick elements of SAP2000 program. A time history load of 7.5 lb/sec was applied at the top, analogous to the support and loading condition of ASTM C78 procedure, and the deflection measured at the center of the beam.

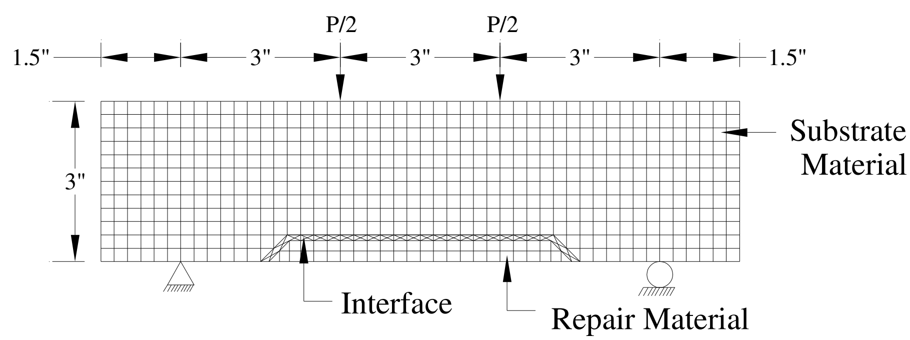


Figure 6.2 Finite Element Model of the Composite Beam

As per the first objective of the FEM, the MOE of the repair material elements in the notch portion and the interface area were assigned the same value as the repair material. While, as per the second objective, a lower value of MOE of the interface area elements with respect to the MOE of repair materials, was assigned to incorporate a weaker bond between the repair and substrate materials. Deflections at the center of the beam were recorded as a function of the decrease in percentage of MOE of the element in the interface area. MOE of the substrate material was assumed 4.5 x 10^6 psi, and the modulus of elasticity of repair materials were varied to achieve a modular ratio (i.e. ratio of modulus of elasticity of repair material to the modulus of elasticity of substrate material) ranging from 1.3 to 0.7, keeping the poisson's ratio of both materials at 0.2. Assuming the selected repair materials would have a range of modular ratio 0.7 to 1.3. However, any difference of MOE magnitude would show similar sort of stress distribution in the composite section. The FEM was analyzed, stress concentrations were plotted and the compatibility between repair and substrate was investigated as a function of the rapidly changing properties of repair materials relative to substrate concrete.

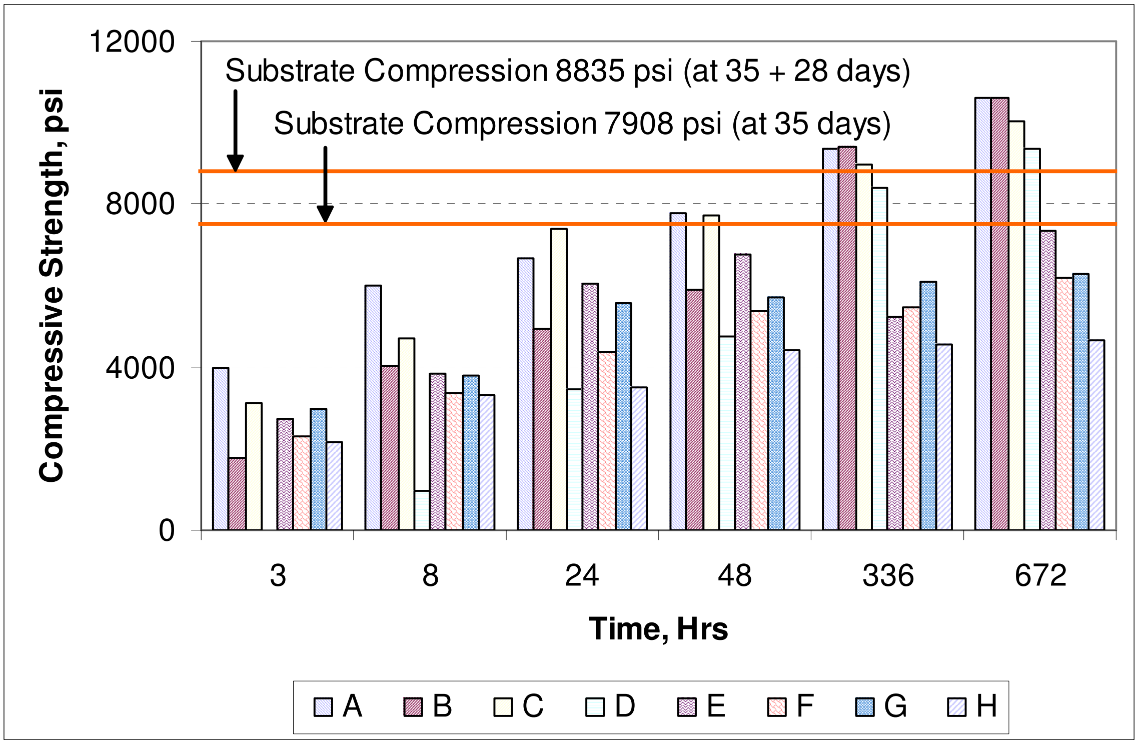
6.5. Results and Analysis

In the present investigation the compressive and the split tensile strength of the substrate concrete at 35 days was found to be 7908 and 730 psi, respectively. It was observed that in the subsequent 28 days during which the composite sections were cured, the substrate concrete registered only an additional 927 psi increase in compressive strength and 161 psi in split tensile strength. In contrast, test specimens of repair materials cast alongside the composite section exhibited a rapid gain in compressive strength and split tensile strength within 28 days, ranging from 31 MPa and 2.7 MPa to 81 MPa and 7 MPa, respectively. Figure 6.3a and b show the development in compressive strength and split tensile strength of the eight repair materials considered in this study. The compressive strength and the split tensile strength of the substrate concrete at 35 days and 35 + 28 days of age are also shown in Figure 6.3a and b for reference, respectively.

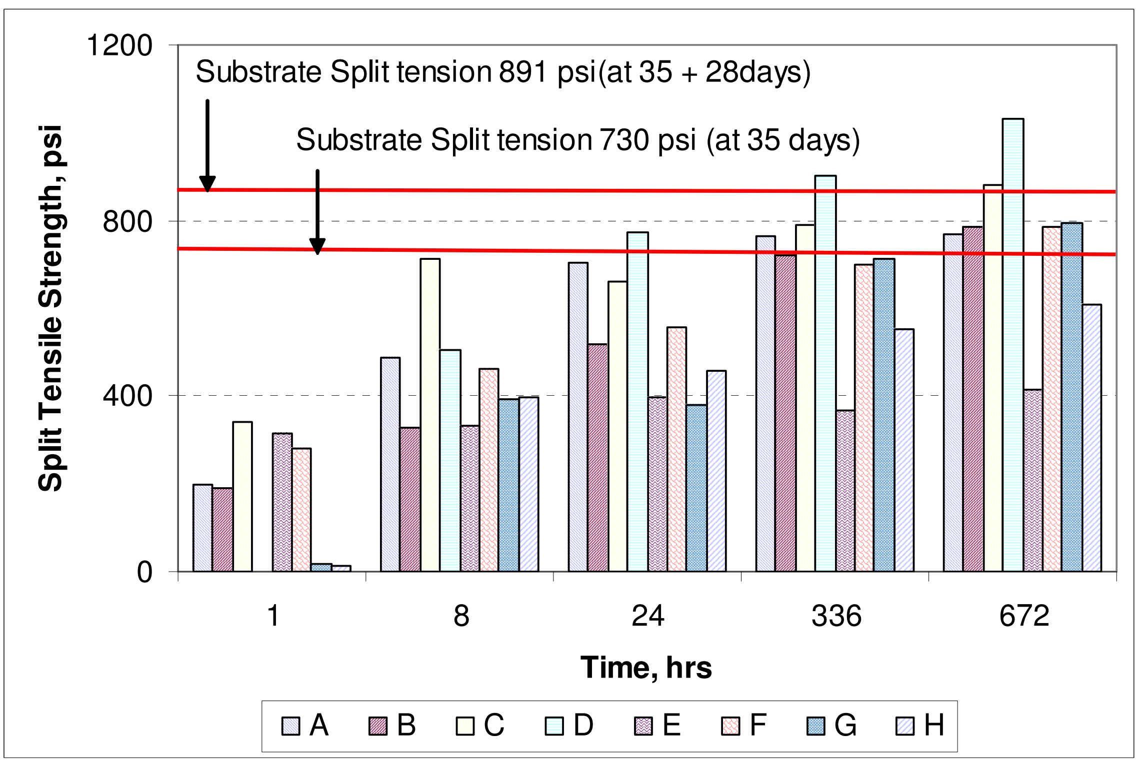
It is apparent from observing the data in Figure 6.3a and b that depending on the specific repair material, significant difference exists between the properties of the repair material and the substrate at any given age. This disparity in strengths can be expected to influence the failure mode. Similarly, the texture of the bonding surface and the curing conditions can be expected to have an influence on the properties of composite sections. The surface texture of the bond area was assumed same for all sections, in this study. Three different curing condition results were investigated.

In conducting the third point load bending tests on the repair materials prisms, three different modes of failures were observed as shown in Figure 6.5. Figure 6.5a shows the failure at the center of the composite section indicating a compatible failure of the repair material (Czarneck et al.1999). Figure 6.5b and c show the failure of the composite section as de-lamination and failure at edge of the notch section indicating an incompatible failure of the repair material.

In this study, a compressive strength ratio and a flexural strength ratio (i.e. strength of repair material/strength of substrate concrete) are defined to characterize the influence of disparity in strength on the failure mode of the composite section. In addition, a composite section ratio (i.e. flexural strength of composite beam/ flexural strength of substrate concrete beam of same dimension) was determined to assess the load carrying capacity of specimens with respect to substrate concrete. Load-deflection curves were plotted to assess the compatibility between the repair and substrate concrete materials.



(a) Compressive Strength development of repair materials with age



(b) Split tensile strength development of repair materials with age

Figure 6.3 Compressive and Tensile Strength Development of the Repair Materials Relative to Substrate Concrete

6.5.1. Criteria for Compatibility

It is well established that a stiffer material deflects less in the flexure test compared to a weaker material under the same loading. In the composite beam, if the compressive strength ratio (compressive strength or repair material divided by compressive strength of substrate concrete) is greater than 1.0, the load-deflection curve should have greater slope than the slope of the load-deflection curve of substrate concrete beam as shown in Figure 6.4. If not, then the load transfer to repair material is not adequate and the repair material is not compatible with the substrate concrete.

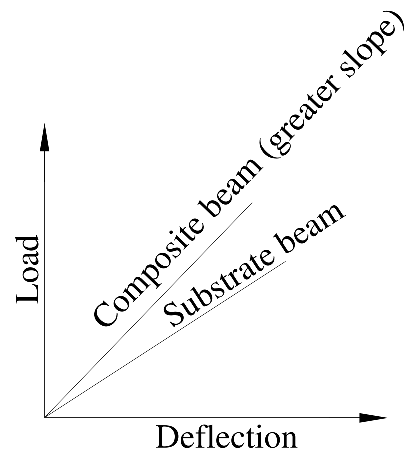


Figure 6.4 Typical Load Deflection Curve of the Composite and Substrate Beam

In case of stiffer repair materials, compressive and flexural strength ratio is typically greater than 1.0; the composite section ratio (Flexural strength of composite beam divided by flexural strength of substrate beam) is expected to be more than 1.0. If not, then the load transfer is not adequate and the repair material is incompatible with the substrate concrete.

In case of weaker repair material, compressive strength ratio and composite section ratio is less than 1.0, and if the load transfer is adequate, the composite beam is forced to fail in the middle third portion of the beam or inside the repair material due to maximum stress induced. If the failure mode is on the edge of the notch or if the repair material is de-bonded, instead of failing in the middle-third of the patched beam, then the repair material is not compatible with the substrate beam.

In case of repair materials where composite section ratio is greater than 1.0, the load carrying capacity is more than that of the substrate concrete. Therefore, the failure mode is immaterial whether it is failing at the middle-third or at the edge of the repair section in the composite beam. The repair material can be assumed to be compatible in those cases within the maximum anticipated stress levels. Results and analysis of these investigations are presented.

(a) Failure at the center

(b) Failure due to de-lamination

(c) Failure at the edge of repair

Figure 6.5 Failure Patterns of Composite Beam

6.5.2. Effect of Differences in Strengths

Tables 6.1, Table 6.2 and Table 6.3 show the 28-days results of the compressive strength ratio, flexural strength ratio, and the flexural strength of composite section for air-cured, moist-cured, and alternate moist and air cure specimens, respectively. Also, the tables indicate the failure type observed in the composite sections. In addition, the corresponding load verses deflection curves of these specimens in the flexure test are shown in the Figure 6.6, Figure 6.7, and Figure 6.8.

It can be observed from Table 6.1, Table 6.2 and Table 6.3 that even though the compressive strength ratios of repair materials A, B, C and E in Table 6.1; A, B, C, D, and F in Table 6.2; and A, B, C, D, F and G in Table 6.3, are greater than 1.0, some of these repair materials show either higher or lower slopes in the load-deflection behavior of composite beams in the flexure test, depending on the specific curing condition. For instance, repair materials C in Figure 6.6 and F in Fig 6.7, showed lower slopes and others show equal or higher slopes. The repair materials that are not deforming adequately with the substrate beam, even though compressive and flexural strengths are more than substrate concrete and showed lower slope in load-deflection, are incompatible with the substrate concrete.

It can be observed from Table 6.1, Table 6.2 and Table 6.3 that the repair material compressive strength ratio less than 1.0 are failing either at the middle-third portion or at the edge. For instance repair materials F and G in the Table. 6.1, the compressive strength ratios 0.72 and 0.68, and the failure occur at the edge and de-laminated, respectively. This indicates that these materials are not compatible with the substrate concrete.

The composite section beam with repair material E in Table 6.1; repair material A, B, E, F and G in Table 6.2; repair materials B and E in Table 6.3, have composite section ratios more than 1.0, which indicate that these sections have more flexural strength than a substrate concrete beam. Therefore, these materials are compatible with the substrate concrete even though repair materials B and F failed on the edge.

6.5.3. Effect of Differences in Curing Methods

Tables 6.1, Table 6.2 and Table 6.3 shows the compressive strength, flexural strength, and the composite flexural strength of the repair materials and composite section in air-cured, moist-cured and alternate moist and air-dry cure conditions, respectively. It can be observed from the data that the compressive and flexural strength ratio of repair and substrate materials under moist-cure and alternate moist and air-dry cure conditions were higher than those observed in air-cure conditions, except for repair material E. The improved compressive strength ratio and the flexural strength ratio in moist cure conditions are also reflected in the nature of the failure observed in the composite beam. For instance, repair materials A, B, F and G exhibited compressive strength ratio of 1.12, 1.12, 0.72 and 0.78 respectively, in air-cured condition (see Table 6.1) and showed incompatible with the substrate concrete. The same repair materials (A, B, F and G) exhibited a compressive strength ratio 1.67, 1.70, 1.16 and 1.04 respectively, in the moist curing (see Table 6.2) and were found to be compatible with the substrate concrete. When subjected to alternate moist and air-dry curing, repair materials A, F and G (see Table 6.3), which were compatible in moist cure condition, were found to be incompatible with the substrate concrete. This indicates that the curing influences the compatibility between the repair and substrate concrete.

Table 6.1 Results of Air-Dry Cured Composite beam Specimens

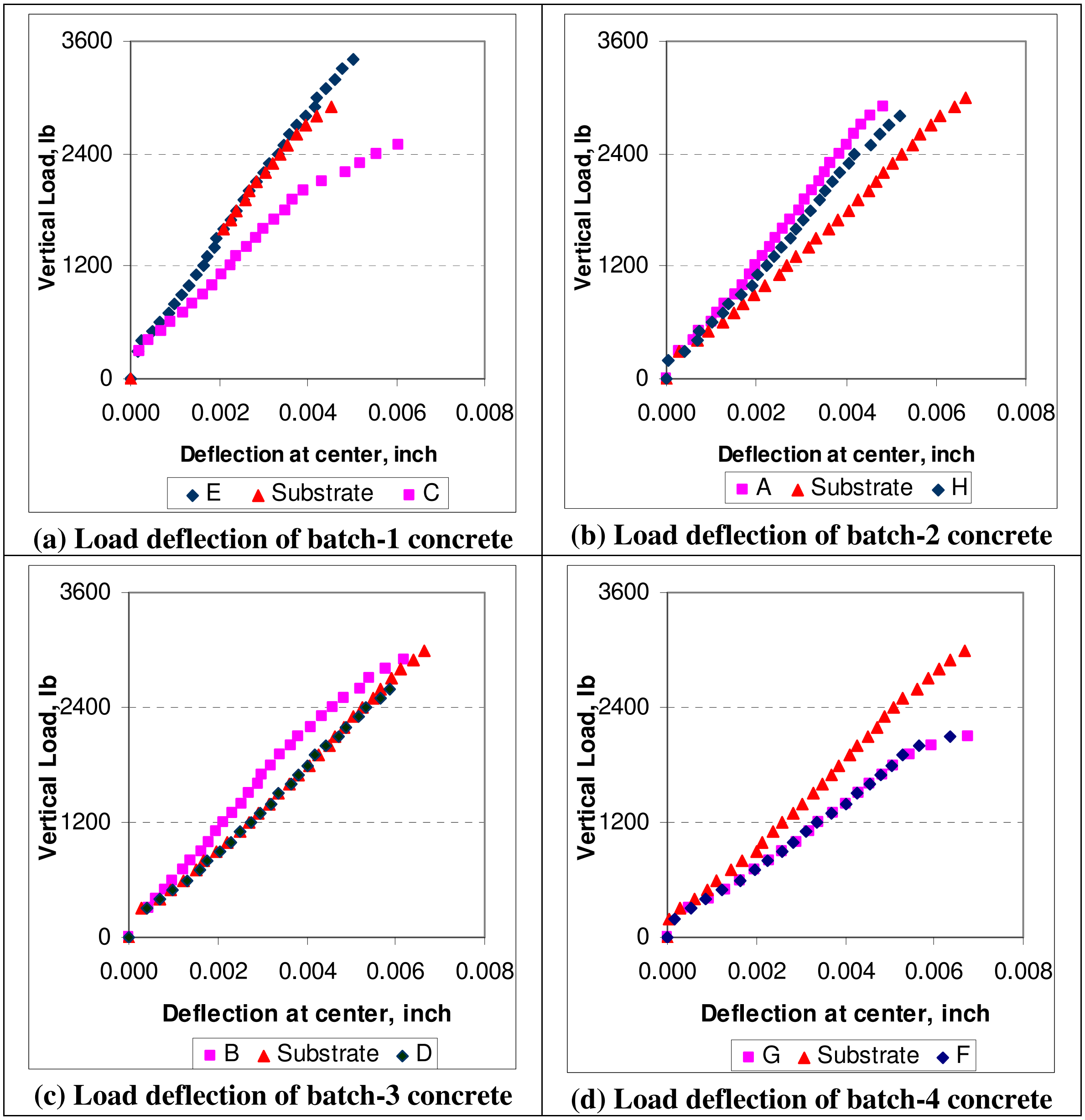
Repair Materials	Repair Material Strength (psi)		Composite Section				Failure at
	Compressive	**Flexural**	**Flexural Strength (psi)**	**Compressive Strength ratio**	**Flexural Strength ratio**	**Composite Substrate ratio**	
A	11050	1986	983	1.12	1.95	0.97	center
B	11020	1938	888	1.12	1.91	0.87	center
C	9363	1981	837	1.02	2.04	0.86	edge
D	9536	2676	892	0.97	2.63	0.88	center
E	9442	1953	1132	1.03	2.01	1.17	center
F	6163	2070	740	0.72	1.95	0.70	edge
G	6703	1527	728	0.78	1.44	0.68	delamination and center
H	6531	1347	937	0.66	1.32	0.92	center

Table 6.2 Results of Moist Cured Composite beam Specimens

Repair Materials	**Repair Material Strength (psi)**		**Composite Section**				**Failure at**
	Compressive	**Flexural**	**Flexural Strength (psi)**	**Compressive Strength ratio**	**Flexural Strength ratio**	**Composite Substrate ratio**	
A	13564	1867	1033	1.67	1.99	1.10	center
B	13857	2131	1142	1.70	2.28	1.22	center and edge
C	11254	2257	797	1.47	2.65	0.93	edge
D	9970	2319	853	1.23	2.48	0.91	edge
E	7507	1431	865	0.98	1.68	1.01	center
F	8453	2151	1242	1.16	2.36	1.36	edge
G	7562	2001	1073	1.04	2.19	1.18	center
H	6613	1448	795	0.81	1.55	0.85	center

Table 6.3 Results of Alternate Moist and Air Cured Specimens

Repair Materials	Repair Material Strength (psi)		Composite Section				Failure at
	Compressive	Flexural	Flexural Strength (psi)	Compressive Strength ratio	Flexural Strength ratio	Composite Substrate ratio	
A	12712	2023	930	1.65	2.16	0.99	center
B	12244	1726	948	1.59	1.84	1.01	Edge
C	11367	2320	792	1.58	2.72	0.93	center and edge
D	10944	2541	888	1.42	2.71	0.95	center and edge
E	7103	1300	1008	0.99	1.52	1.18	center
F	7703	1565	760	1.10	1.71	0.83	Center and edge
G	7083	996	868	1.01	1.09	0.95	center
H	7662	1478	797	0.99	1.58	0.85	center



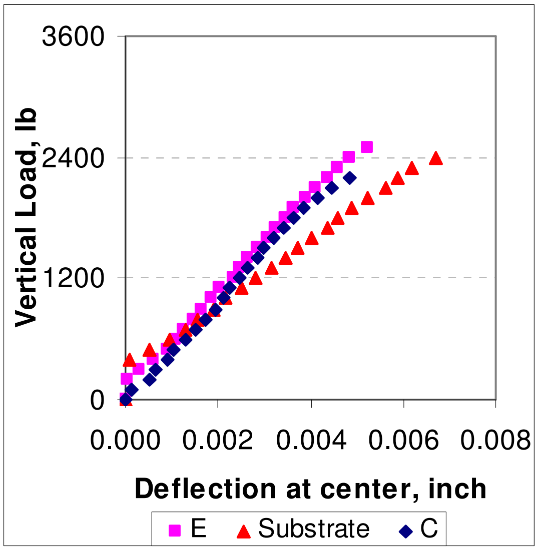
(a) Load deflection of batch-1 concrete

(b) Load deflection of batch-2 concrete

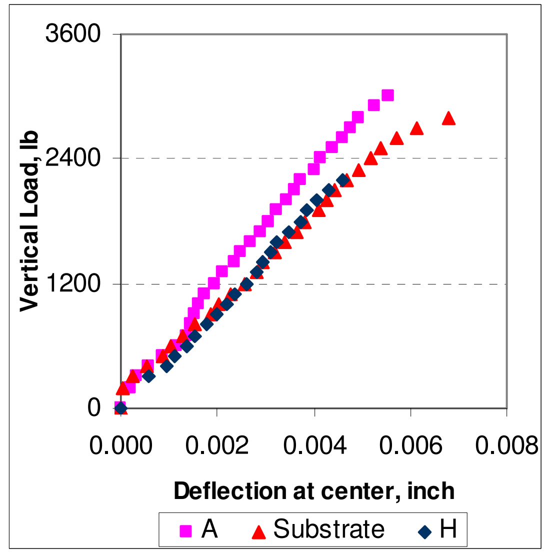
(c) Load deflection of batch-3 concrete

(d) Load deflection of batch-4 concrete

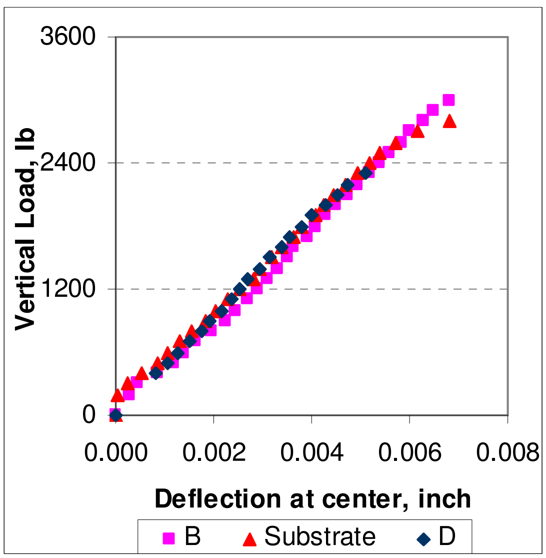
Figure 6.6 Load Deflection Curves of Composite Beam in Air-dry Curing



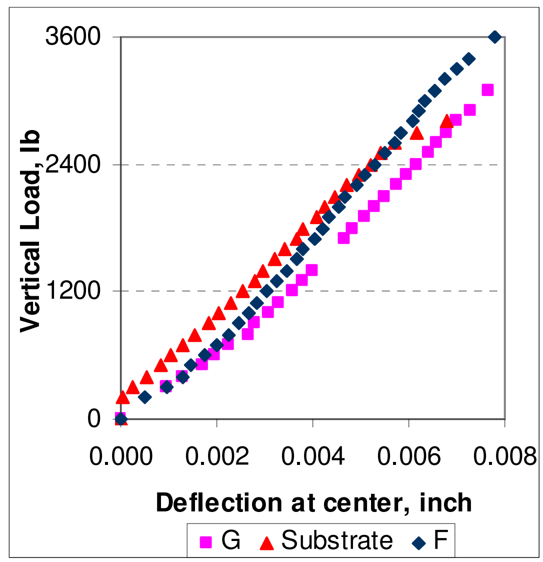
(a) Load deflection of batch-1 concrete



(b) Load deflection of batch-2 concrete

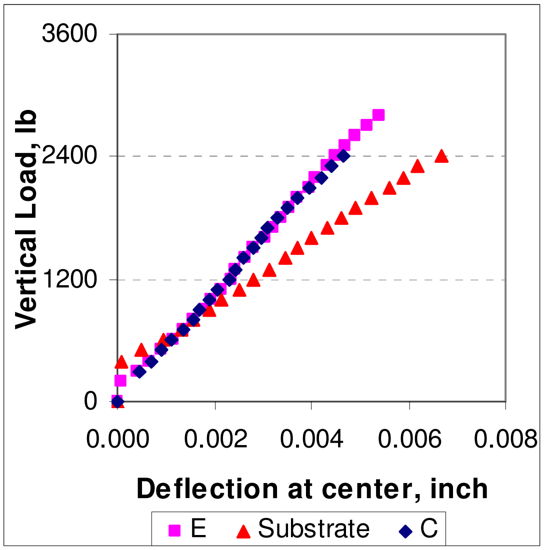


(c) Load deflection of batch-3 concrete

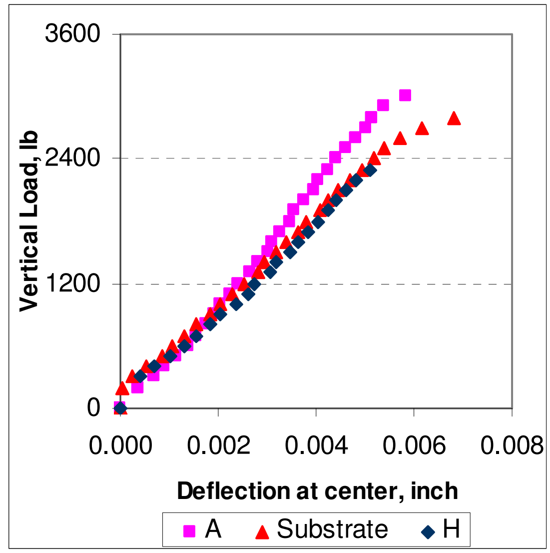


(d) Load deflection of batch-4 concrete

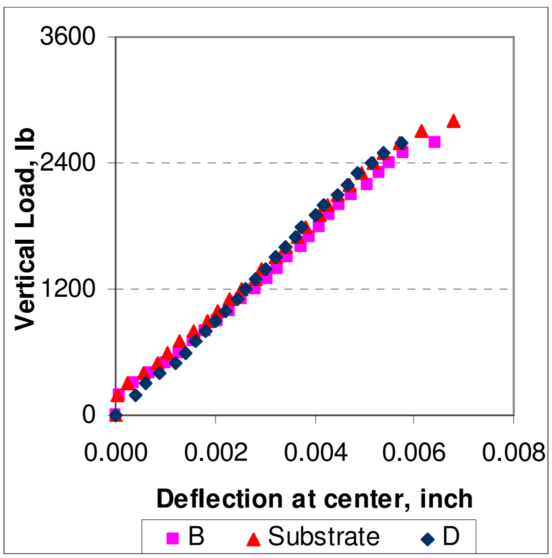
Figure 6.7 Load deflection of Composite Beam in Moist Curing



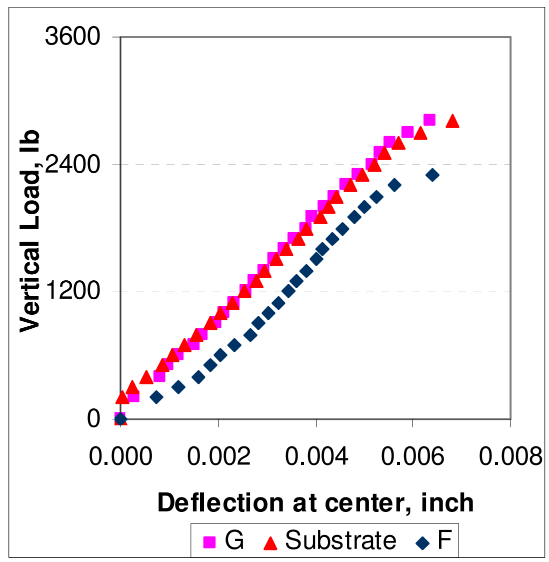
(a) Load deflection of batch-1 concrete



(b) Load deflection of batch-2 concrete



(c) Load deflection of batch-3 concrete



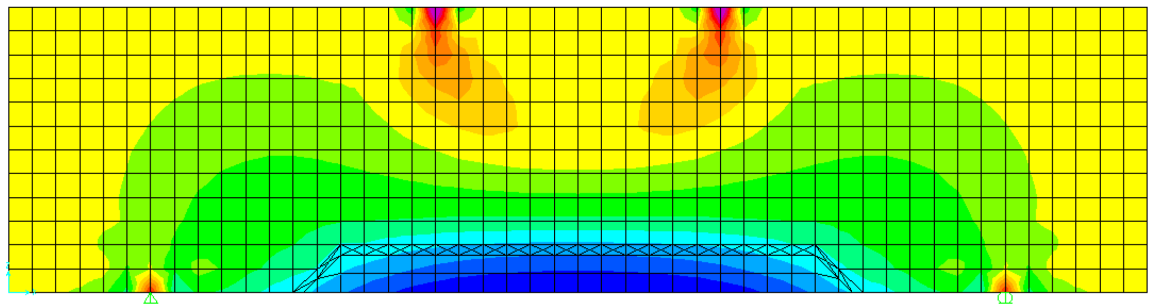
(d) Load deflection of batch-4 concrete

Figure 6.8 Load Deflection Curves of Composite Beam in Alternate Moist and Air-Dry Curing

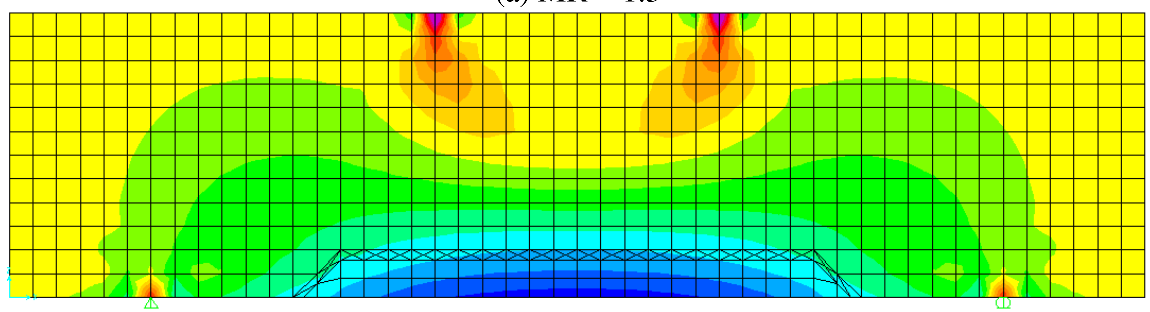
Figure 4.5 shows the drying shrinkage of the repair materials. It can be observed that the repair materials D and G showed high drying shrinkage (i.e. > 0.1% at 28 days) which resulted in incompatible failure in the composite beam test as shown in the Table 6.1. Incidentally, the repair material G, which had highest drying shrinkage value, showed de-bonding in the composite section beam as shown in the Figure 6.5b. Also, the repair materials A, B and C, which have moderate drying shrinkage value (i.e. > 0.05% at 28 days), showed lower composite section ratio (see Table 6.1) even though the compressive and flexural strength ratios are more than 1.0. These materials were found to be incompatible with the substrate concrete. Therefore, drying shrinkage of the repair materials influences the compatibility between the repair and substrate concrete.

6.5.4. Finite Element Analysis

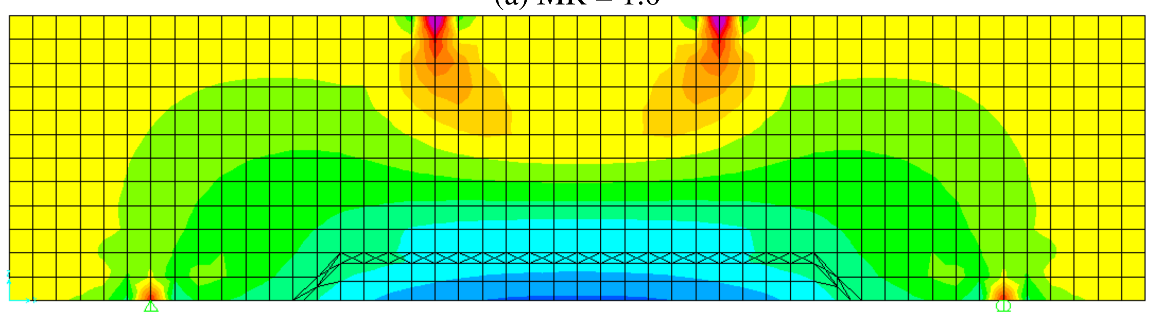
Figure 6.9 shows the distribution of principal tensile stress in the composite section as a function of the modular ratio. It can be observed from Figure 6.9 that as the modular ratio deviates from 1.0, the stress concentration in the composite section is either higher or lower at the bottom fibers as compared to the composite section of modular ratio equal to 1 (i.e. control substrate prism). For instance, when the modular ratio is 1.3, higher tensile stress concentration occurs on the substrate as well as repair material as observed in the Figure 6.9a. This indicates that when the repair material is significantly stronger than the substrate concrete the failure preferentially occurs at center. This is because the repair material cannot deflect to the same extent as substrate concrete (that has a lower stiffness), provided that the bond between the two materials is adequate to transfer the load to the repair material at the bottom. However, when the modular ratio is 0.70, (i.e. the repair material is weaker than the substrate material), the lower tensile stress concentration occurs on the repair material and the substrate. In this case, depending on the bond strength, the failure occurs either at center or at the edge as seen in Figure 6.9a and c. Incidentally, it was observed in the experimental findings that when the repair material is weaker, the bond strength required to transfer the load is lower in magnitude. This situation forces the failure to occur preferentially at the middle third instead of edge.



(a) MR = 1.3



(a) MR = 1.0



(c) MR= 0.7

Figure 6.9 Principal Tensile Stress (in ksi) Distributions in the Composite Beam

Figure 6.10 shows the load-deflection curves of the composite sections. It can be observed in Figure 6.10 that as the stiffness of the repair material increases, the slope of the curve increases. For instance, in case of composite beam with a modular ratio of 1.3, the slope of load-deflection curve is higher than that of a composite beam with a modular ratio of 1.0 and 0.7. This implies that at a particular load, the higher stiffness repair material deflects less as compared to a repair material that has lower or similar stiffness as substrate material; provided the bond is adequate to transfer the load (i.e. interface element MOE is same as the repair material). This finding is similar to the experimental findings.

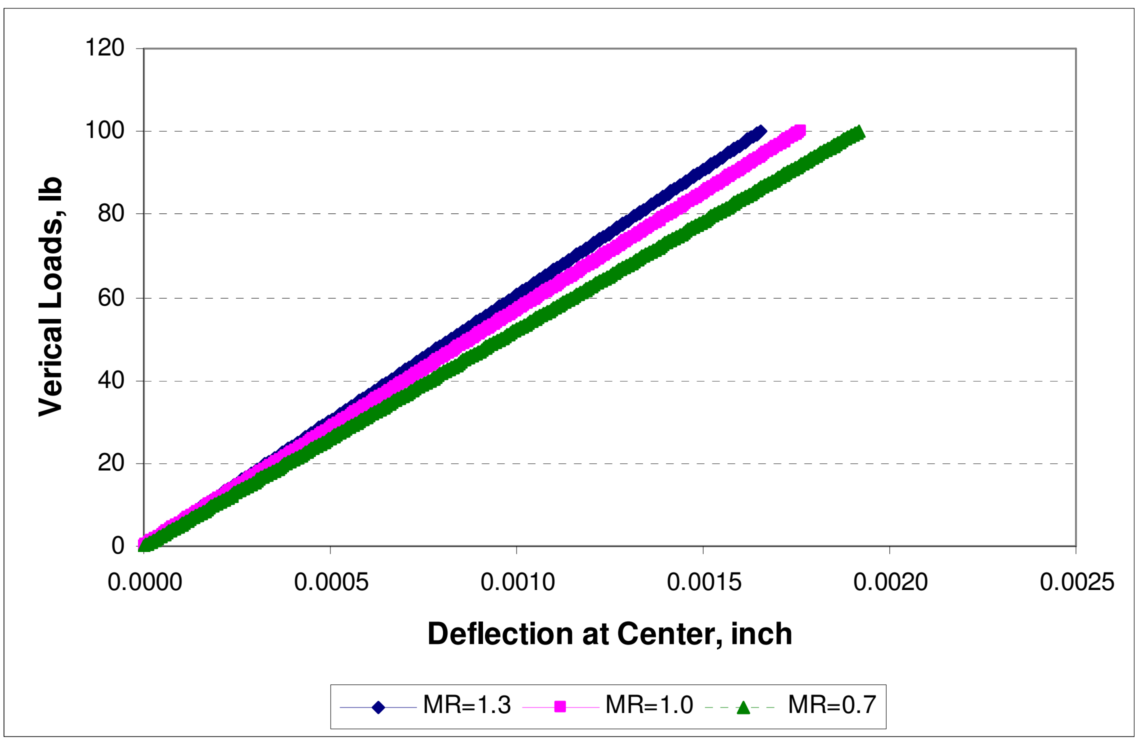


Figure 6.10 FEM deflection at center of the Composite Section with Different Modular Ratios

Figure 6.11 shows the relative increase in the deflection at the center of the composite section when the MOE of the element in the interface area is lowered than that of the repair material. The relative deflection shown in Figure 6.11 is a percentage of the deflection measured at a lower MOE of the interface area element to the deflection measured when the MOE of the interface area element has the same MOE as the repair material. It can be observed in Figure 6.11 that for the modular ratio 1.3; the percentage of deflection increases rapidly as the MOE of the element in the interface area decreases below 10% of the MOE of the repair material. The maximum deflection of the control beam is 6.4% higher than the maximum deflection of composite beam with the repair material of modular ratio 1.3, when the MOE of the interface area is same as repair material. Based on the data presented in Figure 6.11, it is apparent that when the MOE of the interface element drops to about 12% of the MOE of the repair material (i.e. weaker bond strength), then a significant increase in the deflection of the composite beam is observed (well above the deflection of the control beam). Therefore, if the MOE of the elements in the interface area is low, the bond strength is weak; the slope of the load-deflection curve would be lower than the slope of the load-deflection curve of the control beam. In those cases the load transfer through the interface would be inadequate and the repair material will be incompatible with the substrate. This finding validates the experimental findings of repair materials C (see Table 6.1 and Figure 6.6), D (Table 6.2 and Figure 6.7), and F (Table 6.3 and Figure 6.8).

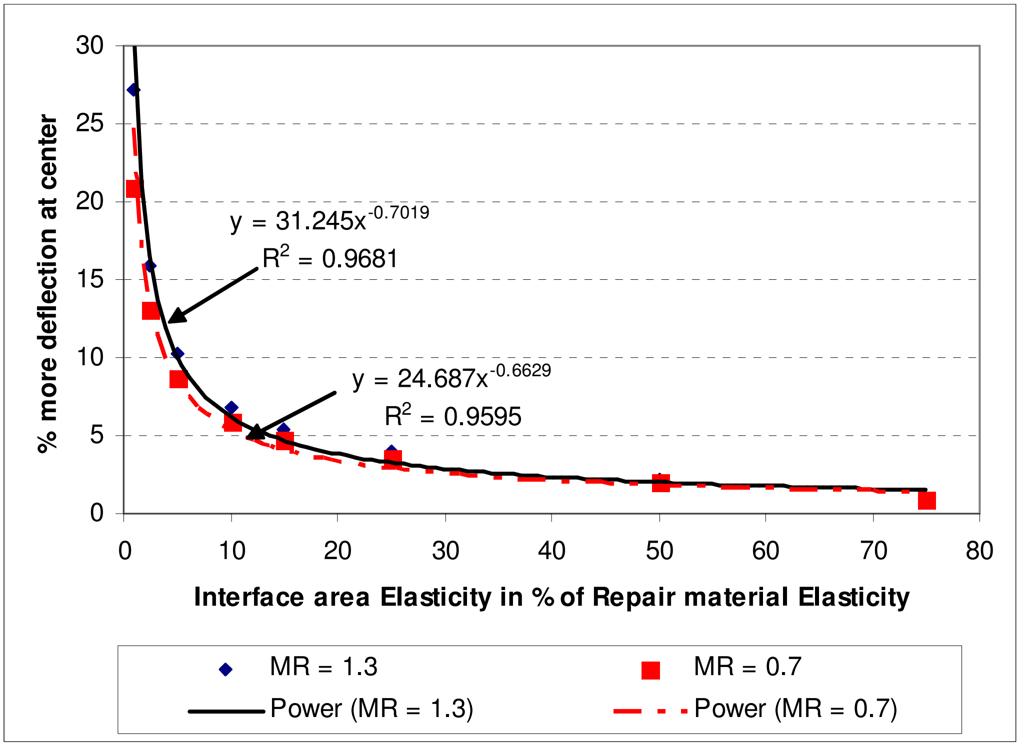


Figure 6.11 FEM Deflections at center due to change in Elasticity of Interface Area

On the other hand, in the lower MOE repair materials the deflection of the composite section is higher than the substrate beam. Therefore, it is difficult to establish a threshold drop in MOE of the interface area element with respect to MOE of the repair material, below which incompatible failures would occur. However, in Figure 6.11 it can be observed for MR 0.7, the relative percentage of deflection increases when the percentage of MOE of the interface area element decreases below 12% of the MOE of the repair material, which is similar to the repair materials of MR=1.3.

6.6. Conclusions

Based on the results from the experimental program and the finite element analysis it can be concluded that not only the compressive strength and the flexural strength ratios are the crucial factors in selecting repair material but also drying shrinkage of the repair materials and load-deflection curve of the composite beam are important to consider before selecting a repair material. Based on the results from the research presented in this paper it is found that for repair materials of higher strength (i.e. compressive and flexural) than the substrate concrete, the load-deflection curve of the composite beam should have a higher slope than the load-deflection curve of substrate concrete beam. For repair materials of lower strength than the substrate concrete, the failure of composite beam should be in the middle-third instead of the edge. Repair materials having higher drying shrinkage (> 0.1% at 28 days) should be moist cured, to avoid incompatible failure.

However, the results from this investigation are limited to eight repair materials and additional data is needed to define more precisely the limits of compressive and flexural strength ratio within which a particular failure mode occurs. Findings from finite element model indicated the importance of modular ratio on the mode of failure in the composite sections and validated the experimental findings. Finally, type of curing also influences the failure mode observed in the composite beams. For a majority of repair materials, moist cured test specimens showed significantly improved compressive and flexural strengths compared to air-cured specimens. The difference in curing regimes therefore caused significant changes in compressive and flexural strength ratios, thereby affecting the failure modes.

CHAPTER SEVEN
CORRELATION OF REPAIR MATERIAL PROPERTIES WITH COMPATIBILITY BETWEEN REPAIR MATERIAL AND SUBSTRATE CONCRETE

7.1. Introduction

To achieve durable repair, it is necessary to consider the repair material properties as part of composite system of repair material and substrate concrete. This chapter investigates the interrelationship of individual repair material properties with the compatibility between repair material and substrate concrete. The composite section ratio as developed to evaluate the compatibility between the repair materials and substrate concrete was used to correlate with individual material properties. The composite section ratio is defined as the ratio of flexural strength of composite beam to that of the control substrate concrete beam. When composite section ratio is greater than 1.0, the load carrying capacity is more than that of the substrate concrete. It is apparent that the repair material is compatible with the substrate concrete under the applied loading condition when composite section ratio is greater than 1. The composite section ratio is influenced by the individual repair material properties. This chapter studies how the Individual properties of repair materials, particularly, compressive strength, flexure strength, bond strength, and drying shrinkage correlate with the composite section ratio of the composite beam.

7.2. Research Significance

Information on individual material properties of repair materials that are affecting compatibility between repair and substrate concrete are limited. For selecting repair materials, most often the studies are conducted on individual repair material properties, rather than studying on the composite section of repair material and substrate concrete. This research investigates how various individual properties particularly; compressive strength, flexure strength, bond strength and drying shrinkage of repair material properties influence the compatibility between repair and substrate concrete. The findings of this research can help the engineers in selecting repair materials for a concrete repair.

7.3. Experimental Test Methods

Following test methods were used to investigate the correlation between repair material properties and compatibility between repair material and substrate concrete. The details of these tests are explained in chapter three.

(a) Compressive Strength

(b) Flexural Strength

(c) Bond Strength

(d) Drying Shrinkage

(e) Third point loading composite beam test

7.4. Experimental Methodology

In this study, the correlation of individual material properties of eight different repair materials with compatibility between repair materials and substrate concrete was investigated by determining specific individual material properties of the repair materials and determining the composite section ratio using a composite beam of repair material and substrate concrete under third point loading. The specific individual properties of the repair materials considered include compressive strength, flexural strength, bond strength and drying shrinkage of the repair materials. Air dry curing condition of the composite specimen after the bonding of the repair material was considered to inflict the drying shrinkage effect into the composite system.

7.4.1. Effect of Compressive and Flexural Strength

In order to investigate the influence of compressive strength and flexural strength of the repair materials on compatibility between the materials, composite section specimens were prepared. The composite sections with a given repair material were prepared on the day when the substrate concrete was 35 days old (28 days moist cured and 7 days air-cured). The composite sections were de-molded 24 hours after casting repair materials, and stored in air-dry curing. Along with the composite sections, cubes and the prismatic sections prepared from the same batch of substrate and repair materials used for evaluating compressive strength and flexural strength. In these tests the repair materials showed very rapid changes in their properties up to 28 days, while the substrate concrete specimens, 35 days earlier than repair materials, did not exhibit significant changes in their compressive and flexural strengths when tested alongside the composite sections. The detail results of these tests are provided in the results section.

As a result of the disparity in the rate of strength gain between the repair materials and substrate concrete, the flexural strength of the composite section (of repair material and substrate concrete) for a given repair material determined at any particular age reflected the influence of a unique combination of properties of the repair and the substrate materials. Depending on the age of testing of the composite section for compatibility, the compressive strength and flexural strength of the repair materials were either lower or higher than the strength of the substrate concrete. This provided a means to evaluate the influence of different mechanical properties of the repair materials on the compatibility of the composite section.

7.4.2. Effect of Drying Shrinkage

By the time the repair materials were cast over the substrate concrete, the substrate concrete would have gone through drying shrinkage, and consequently would exhibit only minimal reversible shrinkage. Drying shrinkage of the repair material relative to substrate concrete induces tensile stresses at the interface between repair and substrate materials, potentially causing failure. This provides a means to correlate drying shrinkage of the repair materials with the compatibility between repair materials and substrate concrete.

7.4.3. Effect of Bond strength

ASTM C 882 test method specifies that the surface of the substrate cylinder should be sand-blasted and dry-brushed before applying the repair material. However, no specific guidance is provided on the quality of the sand to be used in the blasting. Different grade of sand type used in sand blast would provide different types of surface texture. Therefore, two different surface textures were made. One with coarser grit quartz sand (with fineness modulus of 1.73) and another with finer grit quartz sand (with a fineness modulus 1.41). The author understands that the fineness modulus of the sand is not sufficient to characterize the surface texture. However, the objective of this test was to study the qualitative influence of two different surface textures to determine two different bond strengths of a particular repair material. The process of sand blasting itself was identical with both the blasting media use in this study. The two blasting media resulted in two different surface textures that were visually distinguishable. However, no quantitative measurement of the surface roughness was conducted in this research study. With each of the repair material, composite cylinders were cast using substrate specimens prepared with each of the two blasting media. The bond strength was measured at 28 days to assess the effect of the differences in surface texture of the prepared substrate specimen.

Bond strength is an important material property to select a repair material. This provides a means to correlate two different bond strengths of the repair materials with the compatibility between repair materials and substrate concrete.

Table 7.1 Repair Material Properties and Composite Section Ratio

Repair Materials	Compressive Strength (psi)	Flexural Strength (psi)	Bond Strength (psi)		Drying shrinkage (%)	Composite section ratio	Failure mode at
			Fine grit Sand blast	Coarse grit sand blast			
A	11050	1986	2669	3783	0.07	0.97	center
B	11020	1938	2623	3526	0.06	0.87	center
C	9363	1981	1935	2597	0.07	0.86	center and edge
D	9536	2676	1941	3720	0.13	0.88	center
E	9442	1953	3033	3005	0.03	1.17	center
F	6163	2070	2131	1834	0.08	0.7	edge
G	6703	1527	1031	2949	0.23	0.68	delamination and center
H	6531	1347	1749	1926	0.03	0.92	center

7.5. Results and Analysis

7.5.1. Effect of Compressive Strength

Table 7.1 shows the compressive strength, flexural strength, bond strength, drying shrinkage, composite section ratio and the failure modes observed in the specimens. It is generally agreed upon that the potential for cracking of cement based repair materials increases with high compressive strength, despite inherently higher tensile strengths (Mcdonald et al.2002). It can be observed in the Table 7.1 that the composite section ratio of the composite beam with repair material H is 0.92, which is higher than the composite section ratio of the composite beam with repair materials B, C, D, and G (0.87, 0.86, 0.88, and 0.68 respectively), even though the compressive strength of the those materials B, C, D, and G (11020 psi, 9363 psi, 9536 psi, and 6703 psi respectively), were higher than the compressive strength of the repair material H (6531 psi). Therefore, compressive strength of the repair materials is not an appropriate material property to select a repair material for a particular repair.

Figure 7.1 shows the correlation of compressive strength of the repair materials and the composite section ratio. It can be observed that the compressive strength of the repair materials are not significantly correlate with the composite section ratio (R^2=0.2909), although the trend was higher composites section ratio with increased compressive strength of the repair materials.

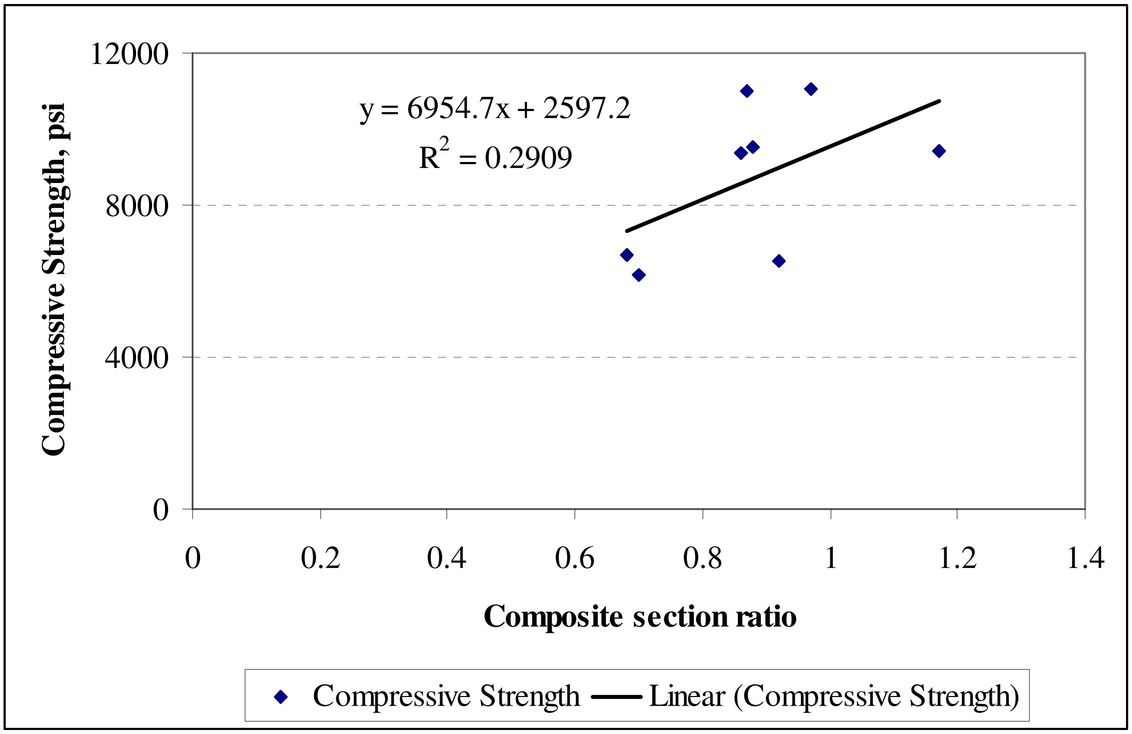


Figure 7.1 Correlation of Compressive Strength with Composite Section Ratio

7.5.2. Effect of Flexural Strength

It can be observed from the Table 7.1 that the composite section ratio of the composite beam with repair material H (0.92) is higher than the composite section ratio of the composite beam with repair materials B, C, D, F and G. (0.87, 0.86, 0.88, 0.7, and 0.68 respectively), even though the flexural strengths of the repair materials (1938 psi, 1981 psi, 2676 psi, 2070 psi, and 1527 psi respectively), were higher than the flexural strength of the repair material H (1347 psi). Therefore, Flexural strength of the repair materials is not an appropriate material property to select a repair material for a particular repair.

Figure 7.2 shows the correlation of the flexural strengths of the repair materials with composite section ratio. It can be observed the flexural strength of the repair materials are not significantly correlate with composite section ratio (R^2=0.01). However, It should be noted that the flexural strength of the repair materials were within a relatively narrow margin (around 2000psi).

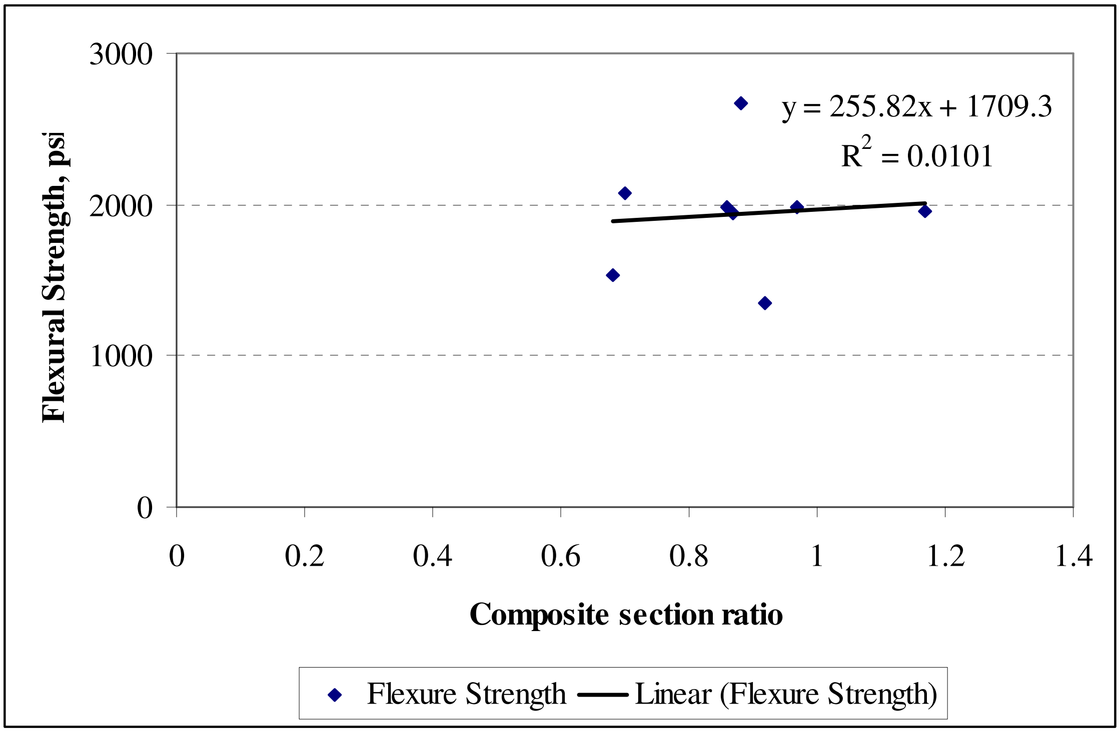


Figure 7.2 Correlation of Flexural Strength with Composite Section Ratio

7.5.3. Effect of Bond Strength

When a compressive load is applied on a composite cylinder in which a repair material is bonded to a substrate material on a slant surface, it is understood that the failure takes place on the weakest plane. In this regard, the texture of the bonding surface is an important parameter that governs the magnitude of the bond strength. Tables 7.1 shows the bond strength data of repair materials in which the slant surface of the substrate specimen was prepared using fine grit sand and coarse grit sand. It can be observed from the data that the bond strength was significantly higher in test specimens in which, the substrate surface was textured with coarse grit sand blast compared to those that were textured with fine grit sand, with exception of repair material F. It should also be noted that the mode of failure in the composite cylinder is also governed by the surface texture. For instance, composite cylinders prepared with repair materials D and E failed at the interface when textured with fine grit sand blast (see Figure 5.4). However, the composite cylinders prepared with same repair materials and cured similarly, did not fail on the interface when textured with the coarse grit sand blast because of the improved bond strength. Composite section with repair material D failed in the substrate mortar. While, the composite section with repair material E failed in the repair material instead of interface. Therefore, the author believe that the ASTM C882 specification should include a requirement to achieve a degree of roughness on the substrate mortar surface, before casting repair material over it. In the present research, the surface texture was evaluated only in qualitative terms. Further work is needed in this regard to quantify the surface texture on the substrate mortar. The minimum bond strength was calculated for the composite sections as per ASTM C882.

Figure 7.3 shows the correlation of bond strength, fine grit sand basted surface and coarse grit sand blasted surface, of the repair materials with composite section ratio of the composite beams. It can be observed there is no significant correlation between the bond strength and composite section ratio. However, the bond strength of the repair materials from fine grit sand blasted section showed improved correlation than the coarse grit sand blasted sections. For instance, fine grit sand blasted sections showed a correlation coefficient of 0.57, while coarse grit sand blasted section 0.09. From the failure modes of the composite section of the slant shear specimens and the correlation coefficient, it can be concluded that the fine grit sand blast surface bond strengths are more indicative of bond strength for the compatibility than the bond strength from coarser grit sand blast sections. Even though, the coarse grit sand blast sections bond strengths were higher than the fine grit sand blast section bond strength.

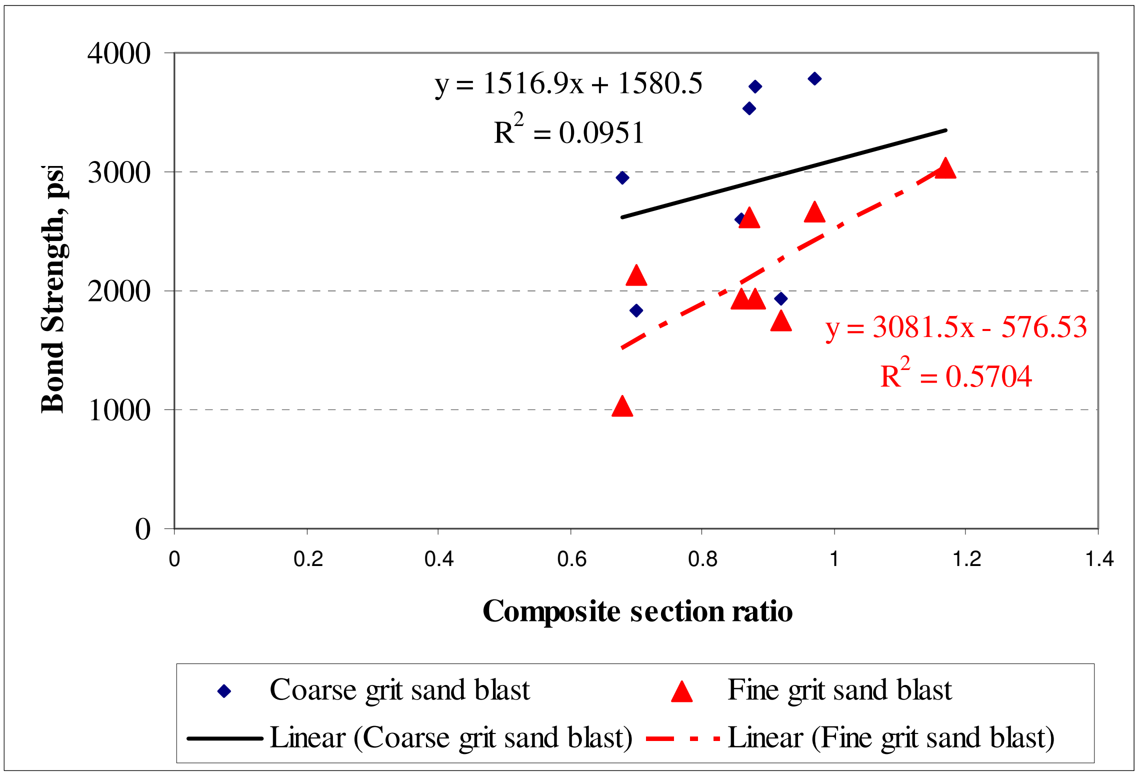


Figure 7.3 Correlation of Bond strength with Composite Section Ratio

7.5.4. Effect of Drying Shrinkage

It can be observed in the Table 7.1, the drying shrinkage of the repair materials D and G (0.13% and 0.23%), and showed high drying shrinkage (i.e. > 0.1% at 28 days) which resulted lower composite section ratios (0.88 and 0.68) in the composite beam test. Incidentally, the repair material G, which had highest drying shrinkage value (0.23%), showed de-bonding in the composite section beam as shown in the Figure 6.5b. Also, the repair materials A, B and C, which have moderate drying shrinkage value (i.e. > 0.05% at 28 days), showed lower composite section ratio (see Table.7.1) even though the compressive and flexural strengths are higher than the substrate concrete.

Figure 7.4 shows the correlation of the drying shrinkage of the repair materials with the composite section ratio of the composite beam. It can be observed there is moderate correlation between the drying shrinkage and composite section ratio (R^2=0.42). However, the trend was for improved composite section ratio with decreasing drying shrinkage of the repair materials. It should be noted that these specimens were air dry cure to inflict the drying shrinkage of the repair materials into the compatibility. Moist curing or other types of curing may not give same sort of correlation.

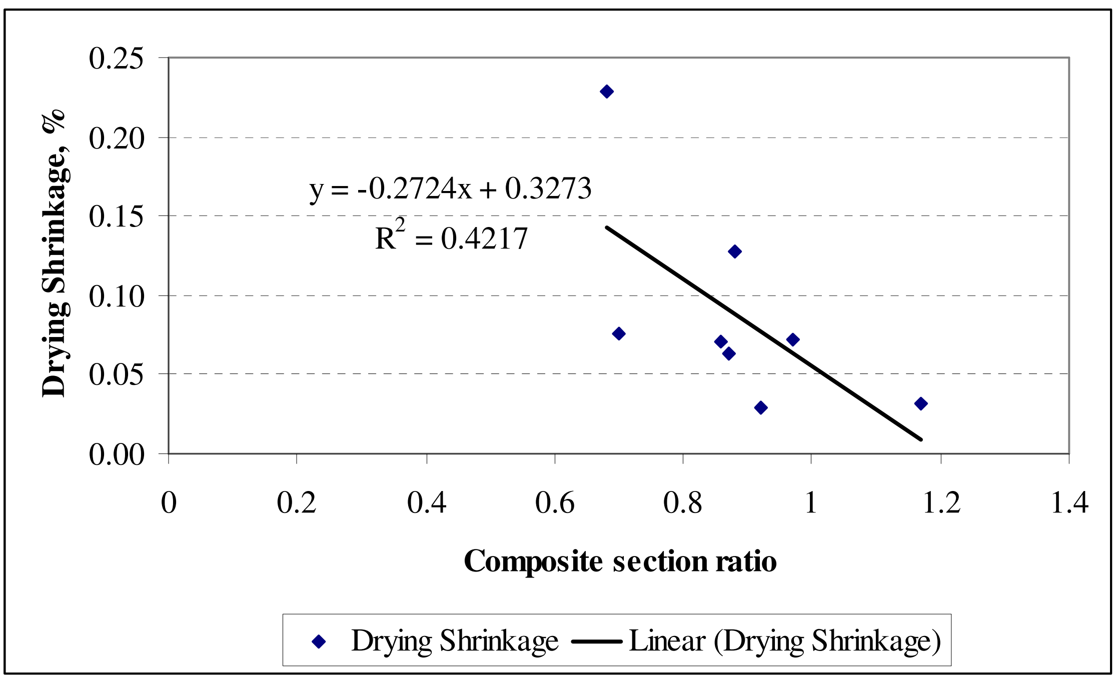


Figure 7.4 Correlation of Drying Shrinkage with Composite Section Ratio

7.5.5. Overall correlation of the material properties

Figure 7.5 shows the overall correlation of the repair material properties with compatibility of the repair material with substrate concrete. It was observed, there was no significant correlation of any individual property of the repair materials. However, it can be observed from all results of material properties, the bond strength determined using fine grit sand blast sections was most correlated with the composite section ratio. Flexural strength of the repair material is the least material property to check before selecting a repair material for compatibility. Even though, the composite beams were tested in flexure.

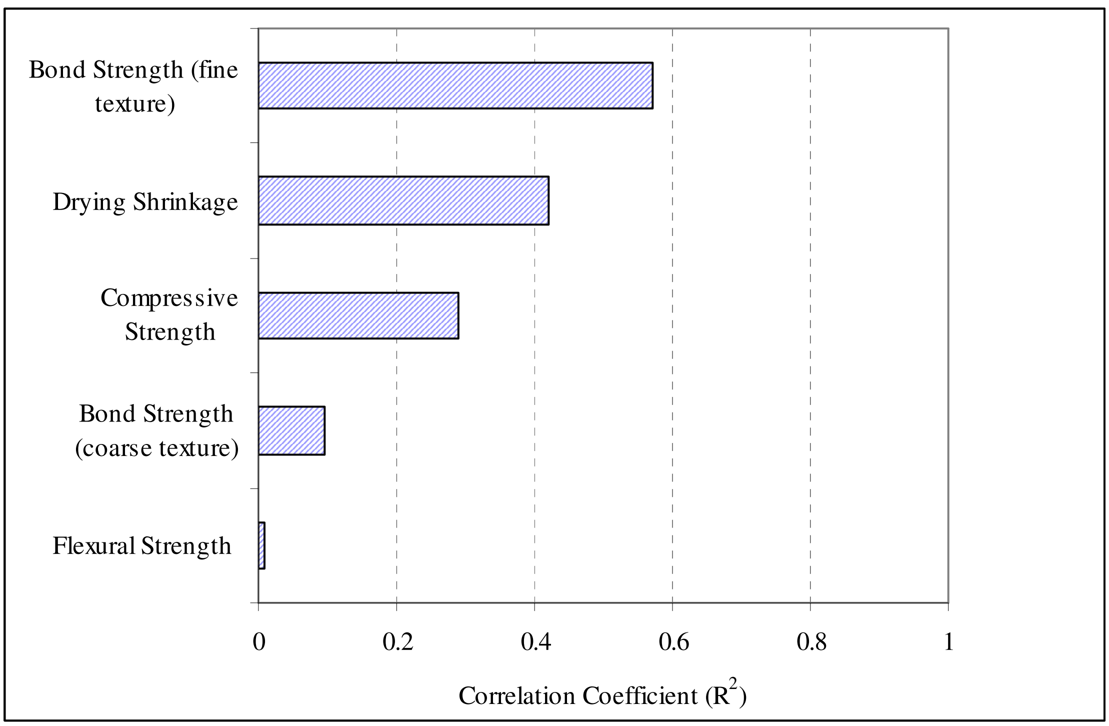


Figure 7.5 Factors influencing the Compatibility Between Repair Material and Substrate Concrete

7.6. Conclusion

Based on the correlation of the repair material properties and the compatibility between the repair material and substrate concrete, it can be concluded that there is no significant relationship between individual material properties with the compatibility. However, based on the correlation coefficient of eight different repair materials, bond strength by slant shear using finer grit sand blast section or the finer surface finish is the important material property to be considered for selecting a repair material for substrate concrete repair. Drying shrinkage of the repair materials is the next important property to be considered when the repair is fully exposed to dry environment. For such exposure conditions lower drying shrinkage repair materials should be more appropriate to select a repair material. Strength properties of the repair materials are not much important to select a repair material. However, compressive strength of the repair materials close to the substrate concrete showed good results in composite section ratios and hence good compatible with the substrate concrete.

These results are from eight different repair materials. Additional data including durability properties such as temperature effect, freeze-thaw resistance etc., are needed to define more precisely the correlation between repair material properties and compatibility between repair material and substrate concrete.

CHAPTER EIGHT
SUMMARY AND PROPOSED TEST METHOD

8.1. Summary

Despite widespread and expanding need for concrete repair, the lack of comprehensive data and suitable guidelines leads to improper selection of repair materials. Although, the present specification ASTM C928, to determine slant shear bond strength includes a mention about surface texture and minimum compressive strength of a substrate mortar to prepare a specimen, it does not specify or provide sufficient guidelines for the surface texture, and relative compressive strength of substrate mortar for a repair material. This leads to different bond strengths for a particular repair material. Higher compressive strength of substrate mortar yields higher bond strength. Similarly, coarser surface texture yields higher bond strength under the same specification of ASTM C928.

The literature suggests that to achieve a long lasting concrete repair, it is essential that the properties of the repair material and the properties of substrate concrete should match properly. However, in the present investigation it was observed that the repair materials that were similar in a specific property with the substrate concrete could differ substantially in other properties. For example, if the compressive strength of the repair material is close to the compressive strength of substrate concrete, flexural strength, bond strength, drying shrinkage, freeze-thaw resistance of the repair material can be significantly different from the substrate concrete. For such differences in the material properties, it is necessary to study the behavior of the composite section of repair material and substrate concrete instead of studying isolated repair material properties.

The repair materials are strongly influenced by the curing conditions. Some repair materials developed superior performance under moist curing; other materials required air-dry curing to achieve good compatibility. Therefore, environmental conditions are important to consider before selecting a repair material. Selection based on mechanical properties without considering service exposure condition would lead to incompatible failure of the concrete repair.

In this investigation, it has been found that individual repair material properties do not correlate well with the compatibility. Therefore, the selection of repair materials based on its individual repair material properties can not predict the durability of the concrete repair. Compatibility study between repair material and substrate concrete is very important before selecting a repair material. At present, there is no established test method to study compatibility between repair material and substrate concrete. The proposed test method will address the compatibility between repair material and substrate concrete. This method would help to select appropriate repair material for a particular deteriorated substrate concrete in the concrete repair industry.

8.2. Proposed Test Method

The compatibility between repair material and substrate concrete should be examined in such a way that the influence of the repair material properties on the behavior of the composite section can be observed under the applied load and environmental conditions. The compatibility should be evaluated by comparing the behavior of control section of substrate concrete with the behavior of the composite section. Also, the failure patterns as observed while testing composite section should confirm the behavioral findings. For instance, de-lamination or de-bonding of the repair material should be noticed in the composite section analysis.

The present study of the compatibility using a composite beam under third point loading flexure test method is a simple and effective test method to select repair materials. In this method, the influence of relative strengths of repair material and substrate concrete can be assessed from parameters such as flexural strength, load deflection curves, and failure patterns of the composite beam. By comparing these parameters of the composite beam to that of the control beam, the compatibility of the repair material and substrate concrete can be established. The composite beam can be conditioned to different environment conditions before loading to check the influence of environment conditions such as freeze-thaw resistance, drying shrinkage, fluctuating temperature, etc., on the compatibility. Therefore, the present method of composite beam under third point loading is a suitable method to investigate all aspects of the concrete repair, inside a laboratory, before selecting the repair material.

CHAPTER NINE
CONCLUSIONS

Based on the results and observations, the following conclusions can be drawn:

1. Due to growing demands in concrete repair industries, many repair materials are now available with a wide range of properties. Individual repair material property such as compressive strength or bond strength or other properties are not sufficient to select a repair material for a particular distress or deteriorated substrate concrete.
2. The rate of change in strength and other properties of these repair materials from the time of casting to ultimate values are rapid and significant.
3. Evaluation of the bond strength or the compatibility between repair materials and the substrate concrete at early ages is not recommended, due to the dynamic changes in the properties of the repair materials with respect to the substrate concrete.
4. Repair materials that were similar in a specific property with the substrate concrete differ substantially in other properties, such as compressive strength if it is close to compressive strength of substrate concrete, flexural strength, bond strength, drying shrinkage etc., were different from the substrate concrete.
5. The bond strength of the repair material and the compatibility between the repair material and substrate concrete was significantly influenced by the relative strengths of the materials, surface texture of bond area, and curing conditions.

6. At present, slant shear bond strength (ASTM C 928) does not provide any guidelines to precisely prepare the substrate mortar on which repair materials will be cast. For a given repair material, depending on the surface texture, relative strengths, and curing condition, the failure is either on the substrate or in the repair material instead of interface.
7. The maximum stress concentration and the failure modes observed in the finite element analysis and experimental methods, for slant shear composite section and the composite beam of the compatibility study, show strong correlations.
8. Relative differences in the properties of repair materials and substrate concrete significantly influence the behavior of the composite beam in flexural strength.
9. The properties of the repair material and, hence, the compatibility between the repair material and substrate concrete is strongly influenced by the curing methodology. While some repair materials developed superior performance under moist curing, other materials required air-dry curing to achieve good compatibility.
10. Individual repair material properties do not appear to provide an adequate measure of compatibility with a substrate concrete. Therefore, the selection based on repair material properties is not adequate to predict the durability of the concrete repair.

CHAPTER TEN
RECOMMENDATION FOR FUTURE STUDY

1. Presently, there is no adequate guidance in ASTM C 928 test method to proportion a substrate mortar based on the properties of the repair materials. It is recommended that relative compressive and tensile strength should be considered in this regard. Similarly, specific guidance in terms of slant surface texture should be provided to achieve a uniform texture before casting repair materials.
2. In this study the Modular Ratio (Modulus of Elasticity of repair material divided by Modulus of Elasticity of substrate concrete) is calculated numerically for the Finite Element Analysis. In the future, the actual modulus of elasticity should be determined to validate the findings.
3. There is no established test method for conducting a compatibility study of the repair material. The present method of examining compatibility is easy and convenient to use. In this study, the influence of relative differences of selected properties (compressive strength, flexure strength, and drying shrinkage) of repair material and substrate concrete were investigated. In future, other properties such as freeze-thaw resistance, temperature effect, etc., can be studied for the durability of the repair in the same experimental setup
4. Correlations were made for eight different repair materials and with four material properties. In the future, more repair materials can be studied with more durability properties.

APPENDIX

(Experimental Results)

Table A1 Results of chloride Ion penetration

Time (minutes)	Chloride Ion penetration in Coulomb Repair Materials							
	A		B		C		D	
	#1	#2	#1	#2	#1	#2	#1	#2
1	6	5	5	6			0	0
30	194	188	190	204			22	23
60	403	393	402	433	357	359	45	46
90	624	608	634	689	561	563	68	70
120	854	831	888	971	776	779	92	93
150	1090	1060	1164	1281	1001	1006	115	117
180	1328	1291	1457	1615	1235	1242	139	141
210	1568	1523	1765	1970	1477	1487	163	164
240	1807	1753	2085	2338	1727	1740	187	188
270	2045	1981	2412	2715	1984	2002	211	212
300	2279	2207	2742	3095	2248	2270	236	236
330	2510	2428	3072	3475	2518	2546	260	261
360	2735	2644	3399	3857	2794	2828	284	285
Average	2690		3628		2811		285	
COV*(%)	2.4		8.9		0.9		0.2	

* Coefficient of Variation

Table A2 Results of chloride Ion penetration

Time (minutes)	Chloride Ion penetration in Coulomb Repair Materials							
	E		F		G		H	
	#1	#2	#1	#2	#1	#2	#1	#2
1	1	1	16	16	17	17	3	3
30	37	39	619	600	681	674	102	108
60	73	77	1357	1321	1570	1560	206	220
90	110	115	2108	2054	2635	2620	313	333
120	146	152	2859	2789	3920	3875	421	449
150	183	190	3608	3522	5545	5406	531	566
180	220	227	4364	4259	7345	7198	642	686
210	257	265	5127	5004	8641	8998	755	807
240	294	302	5899	5745	8641	9518	869	929
270	332	339			8641	9518	984	1054
300	369	376			8641	9518	1100	1181
330	407	413			8641	9518	1219	1310
360	445	449			8642	9518	1340	1442
Average	447		>>4000		>>4000		1391	
COV*(%)	0.6		1.9		6.8		5.2	

* Coefficient of Variation

Table A3 Results of Drying Shrinkage of Repair Material A

Day	Ref.	Comparator Readings (inch)				Drying Shrinkage (%)				Average	COV
	reading	#1	#2	#3	#4	#1	#2	#3	#4	(%)	(%)
0	0.0053	0.2851	0.2709	0.2902	0.2773					0.00	
4	0.0054	0.2815	0.2672	0.2867	0.2738	0.0370	0.0380	0.0360	0.0360	0.04	2.61
11	0.0055	0.2802	0.2658	0.2853	0.2723	0.0510	0.0530	0.0510	0.0520	0.05	1.85
18	0.0051	0.2786	0.2642	0.2838	0.2708	0.0630	0.0650	0.0620	0.0630	0.06	1.99
25	0.0048	0.2775	0.2630	0.2825	0.2697	0.0710	0.0740	0.0720	0.0710	0.07	1.96

Table A4 Results of Drying Shrinkage of Repair Material B

Day	Ref.	Comparator Readings (inch)				Drying Shrinkage (%)				Average	COV
	reading	#1	#2	#3	#4	#1	#2	#3	#4	(%)	(%)
0	0.0058	0.2665	0.3048	0.2822	0.2806					0.00	
4	0.0050	0.2609	0.2989	0.2761	0.2746	0.0480	0.0510	0.0530	0.0520	0.05	4.24
11	0.0048	0.2601	0.2980	0.2752	0.2736	0.0540	0.0580	0.0600	0.0600	0.06	4.88
18	0.0055	0.2603	0.2982	0.2754	0.2736	0.0590	0.0630	0.0650	0.0670	0.06	5.38
25	0.0053	0.2598	0.2978	0.2755	0.2735	0.0620	0.0650	0.0620	0.0660	0.06	3.23

Table A5 Results of Drying Shrinkage of Repair Material C

Day	Ref. reading	Comparator Readings (inch)				Drying Shrinkage (%)				Average (%)	COV (%)
		#1	#2	#3	#4	#1	#2	#3	#4		
0	0.0058	0.3595	0.2688	0.2622	0.2537					0.00	
4	0.0050	0.3549	0.2645	0.2580	0.2494	0.0380	0.0350	0.0340	0.0350	0.04	4.88
11	0.0048	0.3531	0.2631	0.2564	0.2479	0.0540	0.0470	0.0480	0.0480	0.05	6.50
18	0.0055	0.3524	0.2628	0.2558	0.2472	0.0680	0.0570	0.0610	0.0620	0.06	7.33
25	0.0053	0.3513	0.2616	0.2548	0.2462	0.0770	0.0670	0.0690	0.0700	0.07	6.15

Table A6 Results of Drying Shrinkage of Repair Material D

Day	Ref. reading	Comparator Readings (inch)				Drying Shrinkage (%)				Average (%)	COV (%)
		#1	#2	#3	#4	#1	#2	#3	#4		
0	0.0058	0.3241	0.2741	0.2980	0.1745					0.00	
4	0.0050	0.3145	0.2647	0.2887	0.1650	0.0880	0.0860	0.0850	0.0870	0.09	1.49
11	0.0048	0.3107	0.2610	0.2851	0.1614	0.1240	0.1210	0.1190	0.1210	0.12	1.70
18	0.0055	0.3109	0.2612	0.2854	0.1617	0.1290	0.1260	0.1230	0.1250	0.13	1.99
25	0.0053	0.3107	0.2608	0.2849	0.1614	0.1290	0.1280	0.1260	0.1260	0.13	1.18

Table A7 Results of Drying Shrinkage of Repair Material E

Day	Ref. reading	Comparator Readings (inch)				Drying Shrinkage (%)				Average (%)	COV (%)
		#1	#2	#3	#4	#1	#2	#3	#4		
0	0.0053	0.2704	0.3881	0.2857						0.00	
4	0.0054	0.2697	0.3879	0.2856		0.0080	0.0030	0.0020		0.00	74.18
11	0.0055	0.2686	0.3870	0.2846		0.0200	0.0130	0.0130		0.02	26.36
18	0.0051	0.2675	0.3858	0.2830		0.0270	0.0210	0.0250		0.02	12.56
25	0.0048	0.2664	0.3846	0.2822		0.0350	0.0300	0.0300		0.03	9.12

Table A8 Results of Drying Shrinkage of Repair Material F

Day	Ref. reading	Comparator Readings (inch)				Drying Shrinkage (%)				Average (%)	COV (%)
		#1	#2	#3	#4	#1	#2	#3	#4		
0	0.0053	0.2976	0.3205	0.3253	0.3675					0.00	
4	0.0054	0.2932	0.3163	0.3214	0.3626	0.0450	0.0430	0.0400	0.0500	0.04	9.45
11	0.0055	0.2918	0.3142	0.3190	0.3614	0.0600	0.0650	0.0650	0.0630	0.06	3.74
18	0.0051	0.2907	0.3131	0.3178	0.3605	0.0670	0.0720	0.0730	0.0680	0.07	4.21
25	0.0047	0.2899	0.3122	0.3167	0.3596	0.0710	0.0770	0.0800	0.0730	0.08	5.36

Table A9 Results of Drying Shrinkage of Repair Material G

Day	Ref.	Comparator Readings (inch)				Drying Shrinkage (%)				Average	COV
	reading	#1	#2	#3	#4	#1	#2	#3	#4	(%)	(%)
0	0.0054	0.2710	0.3074	0.2944	0.2869					0.00	
4	0.0054	0.2562	0.2929	0.2789	0.2710	0.1480	0.1450	0.1550	0.1590	0.15	4.22
11	0.0056	0.2522	0.2890	0.2743	0.2665	0.1900	0.1860	0.2030	0.2060	0.20	4.96
18	0.0050	0.2499	0.2866	0.2719	0.2640	0.2070	0.2040	0.2210	0.2250	0.21	4.81
25	0.0048	0.2481	0.2848	0.2700	0.2629	0.2230	0.2200	0.2380	0.2340	0.23	3.77

Table A10 Results of Drying Shrinkage of Repair Material H

Day	Ref.	Comparator Readings (inch)				Drying Shrinkage (%)				Average	COV
	reading	#1	#2	#3	#4	#1	#2	#3	#4	(%)	(%)
0	0.0053	0.3660	0.2809	0.3681	0.2598					0.00	
4	0.0054	0.3650	0.2799	0.3672	0.2589	0.0110	0.0110	0.0100	0.0100	0.01	5.50
11	0.0055	0.3641	0.2789	0.3666	0.2580	0.0210	0.0220	0.0170	0.0200	0.02	10.80
18	0.0050	0.3633	0.2780	0.3655	0.2573	0.0240	0.0260	0.0230	0.0220	0.02	7.19
25	0.0048	0.3627	0.2772	0.3648	0.2566	0.0280	0.0320	0.0280	0.0270	0.03	7.71

Table A11 Results of Freeze-thaw test of Repair Material A

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0049	0.2967	0.2962	3813.0	3815.2	3401	3411							
30	0.0040	0.2947	0.2942	3816.5	3819.8	3344	3353	0.01	0.01	9.7	9.7	0.01	10	0.03
60	0.0051	0.2981	0.2979	3821.0	3822.8	3260	3248	-0.01	-0.02	18.4	18.1	-0.01	18	0.96
90	0.0056	0.3011	0.3007	3824.5	3826.7	3271	3260	-0.04	-0.04	27.8	27.4	-0.04	28	0.91
120	0.0050	0.3050	0.3047	3831.5	3833.4	3081	3070	-0.08	-0.08	32.8	32.4	-0.08	33	0.94
150	0.0052	0.3076	0.3072	3834.5	3833.4	2932	2948	-0.11	-0.11	37.2	37.3	-0.11	37	0.36
180	0.0052	0.3152	0.3148	3843.5	3843.9	2922	2911	-0.18	-0.18	44.3	43.7	-0.18	44	0.97
210	0.0049	0.3300	0.3295	3853.5	3854.0	2750	2759	-0.33	-0.33	45.8	45.8	-0.33	46	0.05
240	0.0048	0.3320	0.3333	3853.0	3851.8	2788	2795	-0.35	-0.37	47.0	53.7	-0.36	50	9.37
270	0.0055	0.3331	0.3319	3855.0	3856.1	2791	2783	-0.36	-0.35	53.9	59.9	-0.35	57	7.48
300	0.0061	0.3342	0.3328	3861.0	3861.4	2778	2769	-0.36	-0.35	60.0	65.9	-0.36	63	6.55

*Cycle; † Durability Factor; †† Average

Table A12 Results of Freeze-thaw test of Repair Material B

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0044	0.2737	0.2740	3982.5	3984.7	3689	3679							
30	0.0055	0.2747	0.2752	3980.0	3983.3	3681	3672	0.00	0.00	10.0	10.0	0.00	10	0.04
60	0.0061	0.2742	0.2740	3980.5	3982.3	3701	3713	0.01	0.02	20.1	20.4	0.01	20	0.86
90	0.0051	0.2735	0.2739	3979.5	3981.7	3690	3679	0.01	0.01	30.0	30.0	0.01	30	0.04
120	0.0047	0.2726	0.2723	3981.0	3982.9	3695	3684	0.01	0.02	40.1	40.1	0.02	40	0.04
150	0.0049	0.2735	0.2739	3980.5	3979.4	3648	3664	0.01	0.01	48.9	49.6	0.01	49	1.02
180	0.0040	0.2720	0.2724	3980.5	3980.9	3656	3645	0.01	0.01	58.9	58.9	0.01	59	0.04
210	0.0051	0.2718	0.2723	3979.5	3980.0	3640	3649	0.03	0.02	68.2	68.9	0.03	69	0.75
240	0.0056	0.2735	0.2738	3979.0	3977.8	3604	3597	0.01	0.01	76.4	76.5	0.01	76	0.11
270	0.0050	0.2739	0.2741	3978.5	3979.6	3579	3571	0.00	0.01	84.7	84.8	0.00	85	0.07
300	0.0052	0.2737	0.2733	3976.0	3976.4	3586	3577	0.01	0.02	94.5	94.5	0.01	95	0.03

*Cycle; † Durability Factor; †† Average

Table A13 Results of Freeze-thaw test of Repair Material C

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0049	0.2365	0.3107	3818.0	3836.0	3459	3461							
30	0.0047	0.2357	0.3097	3818.0	3836.3	3461	3465	0.01	0.01	10.0	10.0	0.01	10	0.08
60	0.0051	0.2349	0.3085	3818.0	3836.7	3475	3481	0.02	0.02	20.0	20.2	0.02	20	0.81
90	0.0053	0.2351	0.3087	3818.0	3837.0	3492	3494	0.02	0.02	30.6	30.6	0.02	31	0.00
120	0.0057	0.2360	0.3096	3818.0	3839.7	3471	3482	0.01	0.02	40.3	40.5	0.02	40	0.37
150	0.0051	0.2361	0.3097	3818.0	3838.7	3482	3490	0.01	0.01	50.7	50.8	0.01	51	0.24
180	0.0062	0.2364	0.3100	3818.0	3838.0	3484	3498	0.01	0.02	60.9	61.3	0.02	61	0.49
210	0.0049	0.2352	0.3089	3819.5	3836.5	3488	3458	0.01	0.02	71.2	69.9	0.02	71	1.30
240	0.0055	0.2364	0.3103	3819.5	3838.0	3480	3453	0.01	0.01	81.0	79.6	0.01	80	1.18
270	0.0061	0.2360	0.3102	3817.0	3837.0	3496	3463	0.02	0.02	91.9	90.1	0.02	91	1.42
300	0.0051	0.2350	0.3095	3816.0	3838.0	3503	3458	0.02	0.01	102.6	99.8	0.02	101	1.91

*Cycle; † Durability Factor; †† Average

Table A14 Results of Freeze-thaw test of Repair Material D

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0044	0.2112	0.2115	3707.0	3708.2	3211	3221			0.0				
30	0.0055	0.2136	0.2141	3708.0	3709.3	3190	3181	-0.01	-0.02	9.9	9.8	-0.01	10	0.86
60	0.0061	0.2122	0.2124	3709.5	3710.3	3234	3246	0.01	0.01	20.3	20.3	0.01	20	0.08
90	0.0051	0.2124	0.2128	3709.0	3710.2	3219	3230	-0.01	-0.01	30.1	30.2	-0.01	30	0.04
120	0.0047	0.2103	0.2106	3713.5	3714.4	3245	3234	0.01	0.01	40.9	40.3	0.01	41	0.94
150	0.0049	0.2126	0.2130	3710.5	3711.6	3228	3244	-0.01	-0.01	50.5	50.7	-0.01	51	0.26
180	0.0040	0.2100	0.2104	3713.5	3713.9	3255	3266	0.01	0.01	61.7	61.7	0.01	62	0.04
210	0.0051	0.2105	0.2110	3714.0	3714.5	3263	3272	0.01	0.01	72.3	72.2	0.01	72	0.05
240	0.0056	0.2121	0.2124	3713.5	3714.7	3244	3237	0.00	0.00	81.7	80.8	0.00	81	0.77
270	0.0050	0.2107	0.2109	3714.5	3715.6	3259	3267	0.01	0.01	92.7	92.6	0.01	93	0.09
300	0.0052	0.2105	0.2109	3711.5	3711.9	3268	3259	0.02	0.01	103.6	102.3	0.01	103	0.85

*Cycle; † Durability Factor; †† Average

Table A15 Results of Freeze-thaw test of Repair Material E

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0047	0.2653	0.2648	3535.0	3537.2	2953	2973							
30	0.0049	0.2733	0.2728	3551.0	3554.3	2463	2482	-0.08	-0.08	6.6	6.6	-0.08	7	0.13
60	0.0040	0.2868	0.2866	3509.0	3510.8	407	507	-0.22	-0.23	0.4	0.6	-0.22	0	29.72
90														
120														
150														
180														
210														
240														
270														
300														

*Cycle; † Durability Factor; †† Average

Table A16 Results of Freeze-thaw test of Repair Material F

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0049	0.3278	0.2247	3493.5	3458.0	3017	3037							
30	0.0047	0.3278	0.2244	3491.7	3455.0	3011	3035	0.00	0.00	10.0	10.0	0.00	10	0.19
60	0.0051	0.3285	0.2246	3489.8	3452.0	3002	3020	-0.01	0.00	19.8	19.8	0.00	20	0.09
90	0.0053	0.3287	0.2248	3488.0	3449.0	2962	3058	-0.01	0.00	28.9	30.4	0.00	30	3.58
120	0.0057	0.3304	0.2271	3482.9	3442.3	2978	3021	-0.02	-0.02	39.0	39.6	-0.02	39	1.09
150	0.0062	0.3303	0.2271	3486.0	3447.0	2988	3033	-0.01	-0.01	49.0	49.9	-0.01	49	1.18
180	0.0049	0.3293	0.2258	3481.5	3445.0	2991	3025	-0.02	-0.01	59.0	59.5	-0.01	59	0.66
210	0.0055	0.3303	0.2266	3471.5	3442.5	2994	3014	-0.02	-0.01	68.9	68.9	-0.02	69	0.01
240	0.0061	0.3306	0.2268	3464.0	3436.5	2996	3022	-0.02	-0.01	78.9	79.2	-0.01	79	0.29
270	0.0051	0.3297	0.2262	3434.5	3401.5	2994	3036	-0.02	-0.01	88.6	89.9	-0.02	89	1.04
300	0.0047	0.3295	0.2262	3433.5	3395.0	2993	3030	-0.02	-0.02	98.4	99.5	-0.02	99	0.80

*Cycle; † Durability Factor; †† Average

Table A17 Results of Freeze-thaw test of Repair Material G

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0044	0.2527	0.2530	3584.5	3586.7	2950	2940							
30	0.0055	0.2543	0.2538	3582.5	3585.8	2885	2894	-0.01	0.00	9.6	9.7	0.00	10	0.94
60	0.0061	0.2559	0.2557	3578.5	3580.3	2862	2850	-0.02	-0.01	18.8	18.8	-0.01	19	0.11
90	0.0051	0.2559	0.2563	3576.5	3578.7	2782	2771	-0.03	-0.03	26.7	26.6	-0.03	27	0.08
120	0.0047	0.2560	0.2563	3576.5	3578.4	2771	2760	-0.03	-0.03	35.3	35.3	-0.03	35	0.08
150	0.0049	0.2576	0.2580	3576.5	3575.4	2768	2784	-0.04	-0.04	44.0	44.8	-0.04	44	1.32
180	0.0040	0.2571	0.2575	3573.0	3573.4	2784	2773	-0.05	-0.05	53.4	53.4	-0.05	53	0.08
210	0.0051	0.2578	0.2583	3571.5	3572.0	2808	2817	-0.04	-0.05	63.4	64.3	-0.04	64	0.96
240	0.0056	0.2600	0.2603	3571.0	3569.8	2792	2799	-0.06	-0.06	71.7	72.5	-0.06	72	0.86
270	0.0050	0.2600	0.2602	3570.5	3571.6	2804	2796	-0.07	-0.07	81.3	81.4	-0.07	81	0.08
300	0.0052	0.2605	0.2601	3567.0	3567.4	2805	2796	-0.07	-0.06	90.4	90.4	-0.07	90	0.03

*Cycle; † Durability Factor; †† Average

Table A18 Results of Freeze-thaw test of Repair Material H

Cy*	Ref. reading	Comparator reading		Weight (gm.)		Frequency (Hz.)		Length Change (%)		Durability Factor (%)		Avg††. length change (%)	Avg. D.F† (%)	COV D.F† (%)
		#1	#2	#1	#2	#1	#2	#1	#2	#1	#2			
0	0.0044	0.2776	0.2771	3611.5	3613.7	3004	3014							
30	0.0055	0.2774	0.2769	3616.0	3619.3	2875	2884	0.01	0.01	9.2	9.2	0.01	9	0.03
60	0.0061	0.2775	0.2773	3572.5	3574.3	2800	2788	0.02	0.01	17.4	17.1	0.02	17	1.10
90	0.0051	0.2768	0.2764	3432.0	3434.2	2821	2810	0.02	0.01	26.5	26.1	0.01	26	1.04
120	0.0047	0.2765	0.2762	3334.5	3336.4	2873	2862	0.01	0.01	36.6	36.1	0.01	36	1.03
150	0.0049	0.2773	0.2769	3282.0	3280.9	2934	2950	0.01	0.01	47.7	47.9	0.01	48	0.30
180	0.0040	0.2762	0.2758	3237.0	3237.4	2904	2893	0.01	0.01	56.1	55.3	0.01	56	1.03
210	0.0051	0.2771	0.2766	3210.5	3211.0	2920	2929	0.01	0.01	66.1	66.1	0.01	66	0.03
240	0.0056	0.2781	0.2778	3198.0	3196.8	2925	2932	0.01	0.01	75.8	75.7	0.01	76	0.13
270	0.0050	0.2781	0.2779	3180.0	3181.1	2981	2973	0.00	0.00	88.6	87.5	0.00	88	0.87
300	0.0052	0.2834	0.2830	3171.0	3171.4	2932	2923	-0.05	-0.05	95.3	94.0	-0.05	95	0.93

*Cycle; † Durability Factor; †† Average

Table A19 Results of 28days Flexural Strength in air-dry curing

Specimens	Flexural Strength in psi							
	Repair Materials							
	A	B	C	D	E	F	G	H
#1	1948	2014	1872	2423	1853	2138	1541	1378
#2	2043	1853		2613	1805	1983	1520	1332
#3	1969	1948	2090	2993	2202	2090	1520	1330
Average	1986	1938	1981	2676	1953	2070	1527	1347
COV (%)	2.5	4.2	7.8	10.8	11.1	3.8	0.8	2.0

Table A20 Results of 28days Flexural Strength in moist curing

Specimens	Flexural Strength in psi							
	Repair Materials							
	A	B	C	D	E	F	G	H
#1	1867	2131	2362	2206	1330	2114	2001	1527
#2	1812	2073	2075	2475	1483	2188	1966	1388
#3	1921	2189	2335	2276	1480	2151	2036	1430
Average	1867	2131	2257	2319	1431	2151	2001	1448
COV (%)	2.9	2.7	7.0	6.0	6.1	1.7	1.7	4.9

Table A21 Results of 28days Flexural Strength in alternate moist and air dry curing

Specimens	Flexural Strength in psi							
	Repair Materials							
	A	B	C	D	E	F	G	H
#1	2005	1949	2564	2546	1082	1550	1009	1513
#2	2041	1502	2075	2536	1518	1579	983	1443
Average	2023	1726	2320	2541	1300	1565	996	1478
COV (%)	1.3	18.3	14.9	0.3	23.7	1.3	1.8	3.3

Table A22 Results of 28days Flexural Strength of Composite beam in air dry curing

Specimens	Flexural Strength in psi							
	Composite beam with Repair Materials							
	A	B	C	D	E	F	G	H
#1	990	867	833	907	1123	703	730	893
#2	975	910	840	877	1140	777	727	980
Average	983	888	837	892	1132	740	728	937
COV (%)	1.1	3.4	0.6	2.4	1.0	7.0	0.3	6.5

Table A23 Results of 28days Flexural Strength of Composite beam in moist curing

Specimens	Flexural Strength in psi							
	Composite beam with Repair Materials							
	A	B	C	D	E	F	G	H
#1	1070	1250	793	870	873	1277	1067	753
#2	997	1033	800	837	857	1207	1080	837
Average	1033	1142	797	853	865	1242	1073	795
COV (%)	5.0	13.4	0.6	2.8	1.4	4.0	0.9	7.4

Table A24 Results of 28days Flexural Strength of Composite beam in alternate moist and air dry curing

Specimens	Flexural Strength in psi							
	Composite beam with Repair Materials							
	A	B	C	D	E	F	G	H
#1	1000	873	880	877	1050	767	933	803
#2	860	1023	703	900	967	753	803	790
Average	930	948	792	888	1008	760	868	797
COV (%)	10.6	11.2	15.8	1.9	5.8	1.2	10.6	1.2

Table A25 Compressive Strength of Repair materials A and B in moist cure

Time	Repair Material A				Repair Material B			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	3016	2974	2875	2955	1410	1585	1535	1510
3-hr	4924	5005	5023	4984	2948	3148	3198	3098
8-hr	6097	5672	5622	5797	4198	4503	4493	4398
24-hr	7673	7458	7663	7598	5153	5328	5278	5253
2-days	8114	8282	8306	8234	6989	7464	7714	7389
14-days	9332	9193	9171	9232	9226	8951	9426	9201
28-days	9479	9439	9339	9419	8865	9340	9290	9165

Table A26 Compressive Strength of Repair materials C and D in moist cure

Time	Repair Material A				Repair Material B			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	2980	3022	3121	3041				
3-hr	4278	4359	4377	4338				
8-hr	5795	5370	5320	5495	772	1077	1067	972
24-hr	5803	6313	5758	5958	3152	3327	3277	3252
2-days	5619	5865	5967	5817	4894	5369	5619	5294
14-days	8729	8569	8499	8599	11619	11344	11819	11594
28-days	9813	9793	9353	9653	11429	11904	11854	11729

Table A27 Compressive Strength of Repair materials E and F in moist cure

Time	Repair Material E				Repair Material F			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	5128	5297	5409	5278	1461	1636	1586	1561
3-hr	4968	5768	5968	5568	2141	2341	2391	2291
8-hr	6768	6343	6293	6468	3142	3487	3457	3362
24-hr	6772	7282	6727	6927	4179	4279	4604	4354
2-days	6900	7268	7492	7220	4970	5445	5695	5370
14-days	4456	4296	4226	4326	7154	6879	7354	7129
28-days	4591	4571	4131	4431	7700	8175	8125	8000

Table A28 Compressive Strength of Repair materials G and H in moist cure

Time	Repair Material G				Repair Material H			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	518	476	377	457	116	241	216	191
3-hr	2899	2980	2998	2959	561	761	811	711
8-hr	4094	3669	3619	3794	3680	3985	3975	3880
24-hr	5665	5450	5655	5590	5043	5218	5168	5143
2-days	5576	5744	5768	5696	5094	5569	5819	5494
14-days	6284	6145	6123	6184	6332	6057	6532	6307
28-days	6380	6340	6240	6320	6314	6789	6739	6614

Table A29 Split Tensile Strength of Repair materials A and B in moist cure

Time	Repair Material A				Repair Material B			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	198	216	177	197	180	197	193	190
8-hr	519	464	484	489	309	341	337	329
24-hr	711	694	707	704	501	523	524	516
14-days	773	724	792	763	743	715	708	722
28-days	774	794	736	768	756	803	799	786

Table A30 Split Tensile Strength of Repair materials C and D in moist cure

Time	Repair Material C				Repair Material D			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	352	361	313	342				
8-hr	742	685	706	711	482	516	514	504
24-hr	668	649	663	660	759	783	780	774
14-days	800	750	820	790	923	895	888	902
28-days	885	906	848	880	1003	1050	1046	1033

Table A31 Split Tensile Strength of Repair materials E and F in moist cure

Time	Repair Material E				Repair Material F			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	314	332	293	313	269	286	282	279
8-hr	364	309	329	334	443	475	471	463
24-hr	406	389	402	399	542	564	565	557
14-days	375	326	394	365	722	694	687	701
28-days	421	441	383	415	757	804	800	787

Table A32 Split Tensile Strength of Repair materials G and H in moist cure

Time	Repair Material G				Repair Material H			Average
	#1	#2	#3	Average	#1	#2	#3	
1-hr	24	21	12	19	13	9	14	12
8-hr	425	370	390	395	376	408	404	396
24-hr	389	372	385	382	441	463	464	456
14-days	766	757	865	796	575	547	540	554
28-days	802	562	772	712	578	625	621	608

Table A33 Results of 28days Slant Shear Bond Strength in air-dry curing

Specimens	Slant Shear Bond Strength in psi							
	Repair Materials							
	A	B	C	D	E	F	G	H
#1	3729	3778	2207	3806	3085	1589	2847	1968
#2	3891	3577	3189	3687	2978	1834	3154	1984
#3	3735	3225	2398	3666	2951	1262	2850	1826
Average	3785	3527	2598	3720	3005	1562	2950	1926
COV (%)	2.4	7.9	20.0	2.0	2.4	18.4	6.0	4.5

Table A34 Results of 28days Slant Shear Bond Strength in moist curing

Specimens	Slant Shear Bond Strength in psi							
	Repair Materials							
	A	B	C	D	E	F	G	H
#1	3384	3128	3043	3147	2306	2910	3262	2634
#2	3047	3085	3166	3088	2159	3053	2944	2551
#3	3060	3066	3024	3077	2232	2834	2953	2555
Average	3164	3093	3078	3104	2232	2932	3053	2580
COV (%)	6.0	1.0	2.5	1.2	3.3	3.8	5.9	1.8

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